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GRINNELL GLACIER STUDIES, A PROGRESS REPORT AS RELATED TO CLIMATE

R. A. DIGHTMAN

U. S. Weather Bureau, Helena, Montana

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ABSTRACT

Efforts to obtain data affecting the behavior of Grinnell Glacier, Glacier National Park, are described. Some of the data so far observed, which include precipitation, temperature, runoff from the glacier basin, and actual surveys of the ice body, are tabulated. The possibility that observations to date point toward a renewal of glacier activity in the Northwest is developed. Recent trends toward cooler weather in the northwestern parts of Europe and North America, and wetter weather as well in the case of northwestern North America, are discussed.

1. INTRODUCTION

In an earlier report Dightman and Beatty [1] covered some of the background of the program for measurement and study of some of the glaciers in Glacier National Park. That report contained data through 1951, discussed findings from measurements, and compared observed climatic trends for a 57-year period with glacier behavior and with Willett's [2] tentative forecasts. At a time when many Pacific Northwest glaciers are beginning to show definite growth, as reported by Bengtson [3], Hubley [4], Harrison [5] and others, it is appropriate to report on the first seven years of observations of precipitation and runoff in connection with measurements and observations of the behavior of Grinnell Glacier, Glacier National Park.

While actual measurements of Grinnell Glacier were started by the National Park Service in 1932 at about the time the rate of recession during the first half of the current century was approaching its maximum, and there are photographs of this glacier several years before the turn of the century showing roughly its extent at that time, data on precipitation and runoff for the glacier basin are available only since 1949. The history of the project covered in the earlier report [1] will not be repeated here. The present report will be confined to bringing the earlier summary up to date, to comparing observations with later climate trends, and to discussing the purposes of the work.

2. DEVELOPMENT OF PROJECT SINCE 1950

A Weather Bureau Standpipe Seasonal Storage Precipitation Gage (now known as Grinnell Glacier No. 1), installed on August 27, 1949, about 2,000 feet north-northeast of the location of one of the fronts of the glacier at that time, produced its first seasonal total when the measurement made on July 20, 1950, showed a catch of 125.1 inches. The glacier, located in a cirque opening roughly to the north and northeast, has had its main terminus in recent years in a deep pool at the north end of the cirque, and glacier elevations on September 1, 1950, ran from 6,403 feet (melt pool) to around 7,300 feet at the southern (highest) end. The cirque is bounded on west and south by the Garden Wall, much of which runs between 8,000 and 9,000 ft. in elevation. While the glacier now flows mostly northward, old moraines indicate that at recent maximum size (around 1890) it had an eastward direction of movement at the terminus. Moraines indicate that the storage gage is located only about 100 feet from one earlier extension of the glacier.

This storage gage functioned well until the exceedingly heavy snows of the 1953–54 season resulted in lateral

TABLE 1.—*Precipitation measurements adjacent to Grinnell Glacier, 1950–1956*

Season ending (year and date)	Gage No. 1, Est. 8-27-49 Seasonal total precipitation (in.)	Gage No. 2, Est. 8-15-55 Seasonal total precipitation (in.)
1950—July 20	125.05 (11 mo.)	
1951—July 24	117.59	
1952—July 15	109.27	
1953—July 31	106.93	
1954—Aug. 5	138.20	
1955—Aug. 10	108.22	
1956—Aug. 7	100.11	152.83

TABLE 2.—*Temperature (°F.) at Grinnell Glacier (No. 1) 1951–52*

Year	Month	Average maximum	Average minimum	Average	Highest	Lowest
1951	Aug.*	58.5	39.2	48.9	82	29
1952	Aug.*	64.8	43.7	54.3	79	29

August mean temperatures at nearby stations compared with Grinnell No. 1

Year	Grinnell No. 1 (el. 6,238 ft.)	Summit (el. 5,213)	Babb, 6 NE (el. 4,300)	West Glacier (el. 3,154)	Polebridge (el. 3,690)
1951	48.9	53.2	55.1	60.1	57.0
1952	54.3	54.7	57.0	61.9	58.5

*August was the only complete temperature record month in both years. For period July 25–Sept. 10, 1951 highest temperature 82, lowest 26. For period July 9–Sept. 16, 1952 highest 82, lowest 29.

movement of the snow pack around the gage, damaging the drain assembly, and loosening the concrete foundation. This damage was repaired during the 1955 summer season, an additional 5-ft. section was added to the gage, a larger foundation was built, and the drain assembly was shielded to protect against future lateral movement of snow. At the same time a second gage (Grinnell Glacier No. 2) was installed about 3,000 feet south-southeast of No. 1; No. 2 has the same gage height (21.5 ft.) as No. 1. Windshields are not used on either, as experience during the first two seasons at No. 1 site showed that such shields could not withstand the severe winds in this area.

Establishment of the second gage was expected to show important differences in precipitation, and the first seasonal measurement seemed to verify that expectation (see table 1). Reasons for the larger catch at the new site are probably many, and interrelated in several ways, but it is not unreasonable to observe that since the second site is nearer to the upper end of the glacier, it could have been expected to be in an area of heavier precipitation. There is also some doubt as to the completeness of the No. 1 catch for the season.

During the 1951 and 1952 summer seasons a cotton region shelter, extreme thermometers, and a hygrothermograph were used at the No. 1 site, and a record of daily high and low temperatures was made during those summers only (the shelter was destroyed by porcupines before the 1953 season began). Some pertinent temperature notes appear in table 2. A continuous (throughout the year) temperature record was started by the U. S. Geological Survey in 1951 at the gaging station on Grinnell Creek about a mile from the glacier and about 1,400 feet lower than the melt pool, but little

TABLE 3.—*Runoff from Grinnell Glacier Basin (3.4 sq. mi.), 1950–56*

Water year ending September 30	Runoff in inches of precipitation	Runoff in percent of Grinnell No. 1 precipitation
1950	106.54	85
1951	104.98	89
1952	89.59	82
1953	97.16	91
1954	110.54	80
1955	94.29	87
1956	*102.77	[b]103

* Preliminary, subject to correction.
[b] Indicates that seasonal catch might not have been complete, due possibly to capping or icing of gage orifice. Runoff in 1956 water year was 67 percent of catch of 152.83 in gage No. 2.

work thereon has been done so far. It is interesting to note, in table 2, the differences in average temperature between Grinnell Glacier and nearby stations for the same months.

The U. S. Geological Survey has measured runoff from the glacier basin (3.4 sq. mi.) since 1949, and these data appear in table 3. While the glacier itself currently covers only about 270 acres, its area in 1900 was 600 acres, or just about a square mile. The gaging station on Grinnell Creek could not be located nearer the glacier because of impossible winter operating conditions that exist at other sites. The runoff records are of excellent quality, and reflect in at least some degree the behavior of the glacier. In late summer, for example, the glacier furnishes the larger part of Grinnell Creek's flow.

All these data, including precipitation and temperature observations by the Weather Bureau, temperature and runoff observations by the U. S. Geological Survey, and actual surveys and measurements by the National Park Service, will contribute much to our knowledge of climate and glacier relationships in the years to come—although it must be admitted that 6 or 7 years is certainly not a very long time in which to correlate glacial and climatic behavior, the implications of which correlations may extend into geological time. However, such data as have been accumulated so far already appear to have some significance, considering the well-documented growth of many western North American glaciers during recent years.

3. GLACIER ACTIVITY IN WESTERN UNITED STATES DURING RECENT YEARS

Bengtson [3], Hubley [4], and Harrison [5] have reported increased glacier activity over much of the western United States during recent years. Beatty and Johnson [6], in their annual reports of Glacier National Park glacier observations and measurements, have pointed out that the rapid recession noted during the 1930 and 1940 decades has halted, and since 1950 there has been some evidence of increased glacier activity. Spectacular growth of Coleman Glacier on Mount Baker in the Northern Cascades has been observed, and increased volume of others in this area has been reported. Activity of glaciers has increased as far south as the Central Sierras and as far east as the Northern Rockies. This change in general glacial behavior, covering at least several years over a large area, must

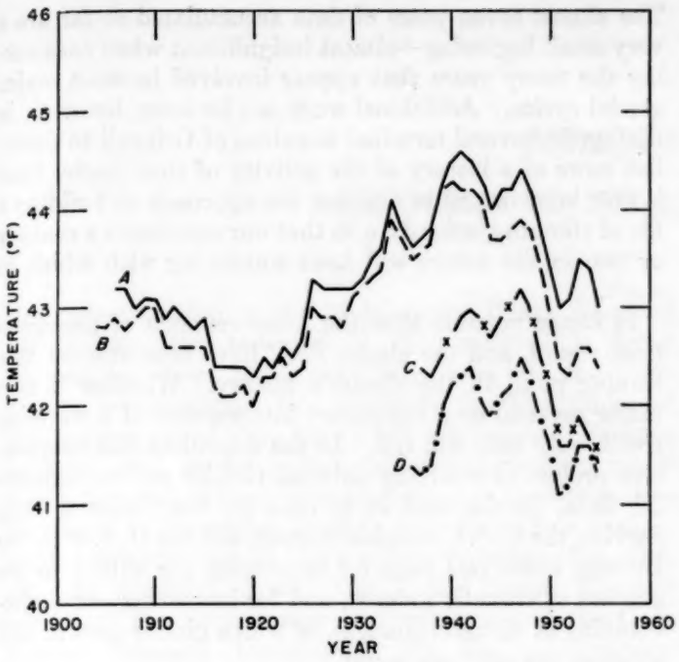

FIGURE 1.—Ten-year moving averages of annual mean temperature, for 10-year periods ending with plotted year, as follows: A. Kalispell (adjusted for change in location 1950), B. Areal average for Montana (weighted), C. West Glacier, and D. Fortine. All are reasonably near (under 60 miles away) to Grinnell Glacier, and reflect observed changes over the last several years.

have some climatic significance. Glaciers in a sense are integrators of climate for several years, i. e., it takes more than one year's weather to make an appreciable contribution to glacial growth or ablation. In this connection it is well to recall Ahlmann's [7] statement, "Glaciers have a tendency to establish time variations of their own that are more or less independent of climatic factors."

4. CLIMATE TRENDS IN THE AREA AROUND GLACIER NATIONAL PARK

In the earlier report [1] 10-year moving averages of average temperature and precipitation for the entire State of Montana were used to establish some short-range trends. In an effort to localize the application of these trends while bringing them up to date through 1955, several 10-year moving averages for single stations are shown in figures 1 and 2. Yearly total precipitation and average temperature data for Kalispell (from which curves A in figs. 1 and 2 were computed) are given in table 4 to enable the reader (1) to see the unsmoothed variations from year to year, and (2) to do his own smoothing by some other method that he may prefer. The similarity of the curves in figures 1 and 2 to the trends shown in [1] is apparent; and the marked agreement of the trends between stations and also between a single station (e. g., curve A) and the 146,000-sq. mi. state areal average (curve B) is noteworthy. They all confirm the observation that the weather around Glacier National Park has been markedly cooler and wetter since about 1946 than

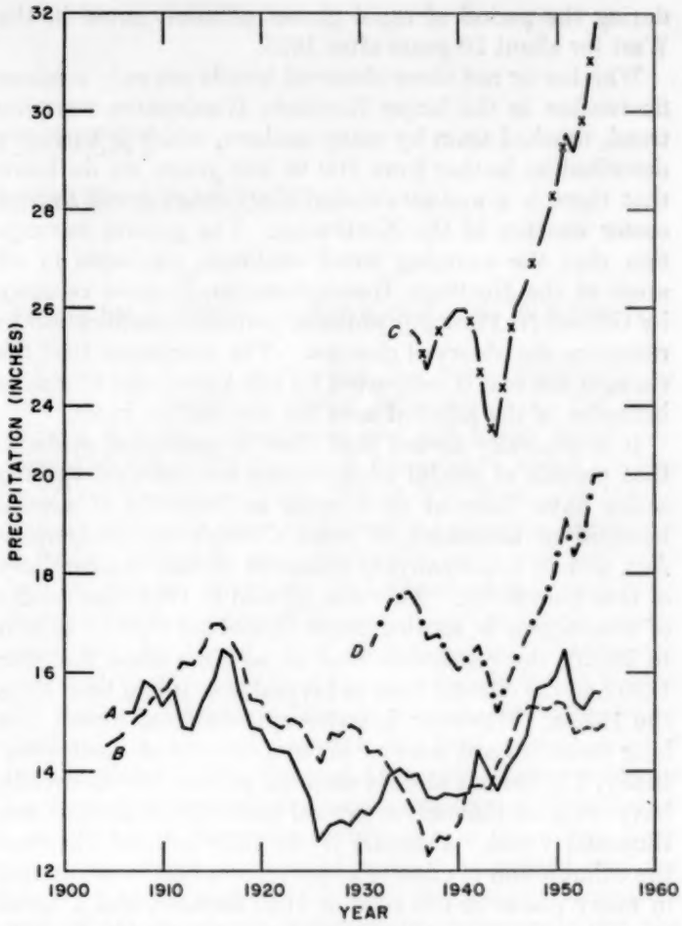

FIGURE 2.—Ten-year moving averages of total annual precipitation, for 10-year periods ending with plotted year, as follows: A. Kalispell (as adjusted), B. Areal average for Montana (weighted), C. West Glacier, and D. Fortine.

TABLE 4.—*Annual precipitation and annual average temperature for Kalispell (Curve A in figs. 1 and 2) 1897–1955. Station move in 1949 made adjustment of last 6 years necessary as new airport location is both wetter and cooler than the former city site. Adjustments were based on the record of a cooperative station located at the city site for two years after the move, and then relocated to the south edge of town*

Year	Total precipitation	Average temperature	Year	Total precipitation	Average temperature
1897	16.99	42.9	1927	18.61	42.0
1898	12.50	44.8	1928	11.94	43.3
1899	19.50	41.0	1929	10.39	41.6
1900	17.09	44.3	1930	15.85	43.2
1901	12.85	43.3	1931	12.31	44.8
1902	19.21	42.2	1932	13.43	43.2
1903	14.63	42.0	1933	18.12	44.3
1904	10.89	44.6	1934	13.74	47.6
1905	15.20	42.8	1935	11.47	42.1
1906	13.50	44.4	1936	14.05	43.1
1907	16.94	42.1	1937	13.80	42.4
1908	18.51	43.5	1938	11.94	45.0
1909	17.80	41.7	1939	11.79	45.4
1910	14.12	44.4	1940	15.06	46.1
1911	16.10	41.7	1941	13.53	45.7
1912	11.70	42.4	1942	20.81	43.0
1913	13.97	41.2	1943	14.17	42.1
1914	17.07	43.6	1944	10.42	44.4
1915	18.75	43.7	1945	15.96	44.4
1916	19.66	39.2	1946	16.10	43.9
1917	16.02	42.4	1947	18.73	44.1
1918	11.15	43.5	1948	20.91	42.4
1919	11.12	42.2	1949	12.48	42.0
1920	12.81	42.9	1950	16.63	41.3
1921	13.13	43.4	1951	20.47	40.8
1922	10.97	41.7	1952	8.79	43.5
1923	12.99	43.3	1953	12.31	45.7
1924	12.83	42.6	1954	14.50	42.7
1925	12.56	45.8	1955	15.83	40.2
1926	13.35	44.9			

during the period of rapid glacier ablation noted in the West for about 20 years after 1925.

Whether or not these observed trends are only a minor fluctuation in the larger Northern Hemisphere warming trend, touched upon by many authors, which is variously described as lasting from 100 to 200 years, we do know that there is a well-established short-range trend toward cooler weather in the Northwest. The general assumption that the warming trend continues unabated in all areas of the Northern Hemisphere (made most recently by Gilbert N. Plass [8]) probably requires qualification to recognize the observed changes. The conclusion that the changes are real is supported by our knowledge of glacier behavior in the affected area for the last 10 years.

It is generally agreed that there is geological evidence that periods of glacial advance and recession on varying scales have followed each other at intervals of several hundred or thousands of years through the Pleistocene Age, and an accompanying change in climate is a corollary of that knowledge. Ahlmann [9] said in 1948 that results of excavations in southernmost Greenland seemed to him to justify the conclusion that at no time since the year 1400 had the climate been so favorable as it had been since the 1920's. However, it seems reasonable to expect this long trend toward warmer climate to reverse itself even tually, if it has not already done so, as such trends already have reversed themselves several times within the last few thousand years. Ahlmann [7] in 1953 pointed out that the culmination of climate improvement had been reached in many places in the 1930 or 1940 decades, and a trend to colder climate had started in northwestern Europe. The important question, which probably will have to wait many years for an answer, is, "Is the trend actually reversing itself in northwestern Europe and in northwestern parts of the North American Continent?" The extent to which we can answer that question now seems to be that the warming trend has suffered at least a temporary interruption over sizable areas.

The periods with which we are working are extremely small on the scale of geological time. It will be many years, perhaps as many as 200 or 300, before our file of climatic information will contain data for a long enough period to permit reasonably full correlation between climate and glaciation. In the meantime, it appears that our knowledge of the history of climate can be increased by additional studies leading to a more complete picture of glacier activity during the last thousand years or so. Ahlmann [7] said "The relations between glaciers and climate are highly complicated and still far from clear. Until we have solved the problems of the existence and variation in size of glaciers, their structure, movement, and other features, we cannot fully utilize them as the climatological registers they really are."

SUMMARY

The work done so far on Grinnell Glacier is a start toward eventual accumulation of sufficient data for studies of the relationships between glacier and climate behavior in the Glacier National Park area of the United States. The almost seven years of data accumulated so far are a very small beginning—almost insignificant when considering the many years that appear involved in most major glacial cycles. Additional work can be done, however, in dating the several terminal moraines of Grinnell to establish more of a history of the activity of that glacier than is now known, and in defining the approach to building a file of climate-glacier data so that our successors a century or two in the future will have something with which to work.

It seems possible that the measurements of precipitation, runoff, and the glacier itself have been started at a turning point in the glacier's history. Whether it is a major reversal or a temporary interruption of a warming trend, only time will tell. In the meantime this cooperative project of studying Grinnell Glacier and accumulating data, participated in to date by the National Park Service, the U. S. Geological Survey, and the U. S. Weather Bureau, holds real hope for improving our ability to use glaciers as climatic indexes, and for increasing our understanding of climatic changes, of which glacier growth and ablation are only one result.

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ANNOUNCEMENT

EXTENSION TO THE STANDARD ATMOSPHERE

A new extension to the 20 kilometer ICAO Standard Atmosphere (the accepted U. S. standard) is being adopted by about 23 United States scientific and engineering organizations; this extension provides tables of atmospheric parameters up to 300 kilometers. Because of their great need for such tables and because many have active high altitude research programs, these organizations met in November 1953 to seek agreement upon a single representation of the atmosphere compatible with the best available data. The United States Weather Bureau of the Department of Commerce and the Geophysics Research Directorate, Air Force Cambridge Research Center of the Air Research and Development Command, co-sponsored this movement which included the following participants:

Air Research and Development Command
*Air Technical Intelligence Center
Air Weather Service
Applied Physics Laboratory
Ballistics Research Laboratory
Boston University (member transferred to Sylvania)
Bureau of Aeronautics, USN
Civil Aeronautics Authority
CONVAIR, San Diego
CONVAIR, Fort Worth
Geophysics Research Directorate (AFCRC)
Harvard College Observatory
*International Civil Aviation Organization
Jet Propulsion Laboratory
National Bureau of Standards
Naval Proving Grounds
Naval Research Laboratory
Office of the Chief Signal Officer
The Rand Corporation
Redstone Arsenal (ABMA)
Signal Corps Engineering Laboratory
United States Weather Bureau
White Sands Proving Grounds
Wright Air Development Center

A working group was appointed to study the problem. This group met several times since 1953 and recommended the basic values and parameters shown in table 1. These values have now been approved by nearly all the participants listed above. A curve of T_M vs. H is shown in figure 1.

*Observer

Extensive tables expanding the basic framework of table 1 are currently under preparation at the Geophysics Research Directorate and will follow closely the format of the ICAO Standard Atmosphere which appears as ICAO Document 7488, NACA TN 3182, and NACA Report 1235; moreover additional information, important at higher altitudes, such as gravity ratio and molecular weight will be included. Supplemental information to describe the variability of the atmosphere and other parameters will be issued later as appendices. Preliminary copies of these tables, in a form analogous to the NACA TN 3182 should be available in limited quantities during 1957. It is planned to have the final edition printed by the Government Printing Office and made available to the public through the Superintendent of Documents.

By virtue of the wide participation in this effort, these 23 organizations established a U. S. standard and are planning action through the Air Coordinating Committee and ICAO to obtain international acceptance for the lowest portion (20 to 32 kilometers) of the tables. In

Table 1.—United States extension to the standard atmosphere

H (m′)	Z (m)	L (°/m′)	T_M (°K)	T (°K)	M (gr/mole)	P (mb.)
0.00	0.00		288.16	288.16	28.966	1.01325×10^{3}
		−0.0065				
11,000.0	11,019		216.66	216.66	28.966	2.2632×10^{2}
		0.0000				
*20,000.0	20,063		216.66	216.66	28.966	5.4748×10^{1}
		0.0000				
25,000.0	25,099		216.66	216.66	28.966	2.4886×10^{1}
		0.0030				
*32,000.0	32,162		237.66	237.66	28.966	8.6776×10^{0}
		0.0030				
47,000.0	47,350		282.66	282.66	28.966	1.2044×10^{0}
		0.0000				
53,000.0	53,446		282.66	282.66	28.966	5.8320×10^{-1}
		−0.0039				
75,000.0	75,895		196.86	196.86	28.966	2.4521×10^{-1}
		0.0000				
90,000.0	91,294		196.86	196.86	28.966	1.8154×10^{-2}
		0.0035				
126,000.0	128,548		322.86	**278.88	**25.02	1.4510×10^{-2}
		0.0100				
175,000.0	179,954		812.86	**686.13	**24.45	6.1895×10^{-3}
		0.0058				
300,000.0	314,859		1537.86	**1024.67	**19.30	1.4473×10^{-4}

*Top of current ICAO Standard and top of recommended extension for standardization—no discontinuity in temperature-height curve.
**Approximate values subject to minor revision depending upon recomputation of M above 90 km.
Z = Altitude in geometric meters
H = Altitude in geopotential meters
L = Temperature lapse rate in Kelvin degrees per geopotential meter
T_M = Molecular-scale temperature in degrees Kelvin
T = Real kinetic temperature in degrees Kelvin
M = Molecular weight in grams per mole
P = Pressure in millibars

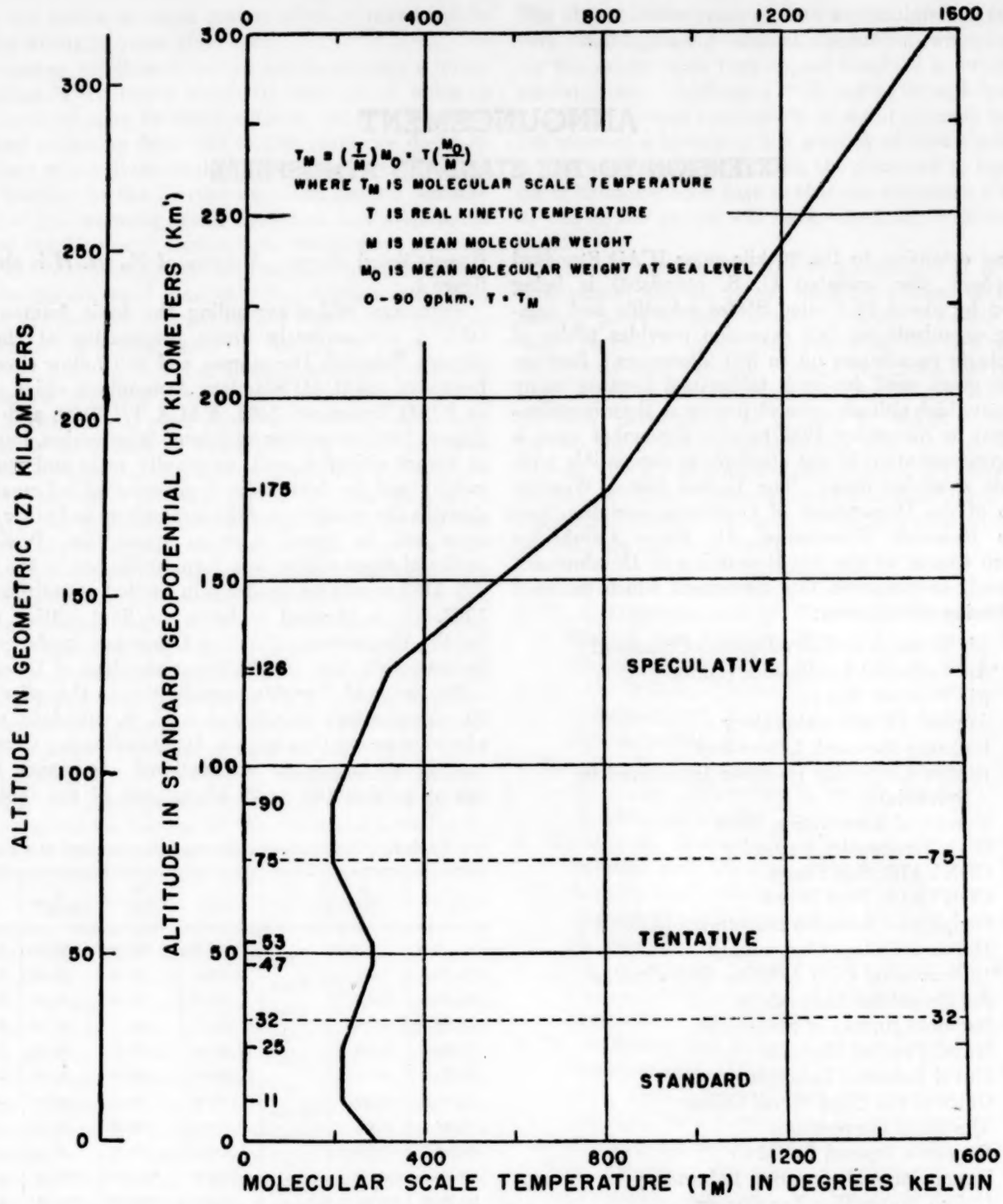

FIGURE 1.—Molecular scale temperature versus geopotential altitude.

this regard, it should be noted that the 75 to 300 kilometer interval of the extension is termed "Speculative Atmosphere," since it is felt that new experimental data obtained over the next five or ten years may lead to a better representation. The interval 32 kilometers to 75 kilometers has been termed "Tentative Atmosphere," since more data may also lead to modification and also because any drastic change in the "Speculative Atmosphere" may require some change in the adjacent lower levels. The 20 to 32 kilometer interval is termed "Standard," since it is a good compromise between the voluminous radiosonde data of the meteorological services and tables already firmly entrenched in the development of engineering equipment. No changes are foreseen for this interval.

Geophysics Research Directorate scientists, R. A. Minzner, and W. S. Ripley, are now preparing the completed report.

Harry Wexler; *Norman Sissenwine*
USWB *GRD, AFCRC*
Co-Chairmen

Committee on Extension to the Standard Atmosphere, U. S. Weather Bureau and Geophysics Research Directorate (AFCRC), Co-sponsors

Oct. 26, 1956

THE WEATHER AND CIRCULATION OF SEPTEMBER 1956[1]

Including a Discussion of Hurricane Flossy and September's Typhoon Tracks

HARRY F. HAWKINS, JR.
Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

1. THE GENERAL CIRCULATION

The 700-mb. circulation of September 1956 was characterized by above normal westerlies at middle latitudes, near normal westerlies to the north, and a stronger and more extensive than normal easterly belt in the Tropics. Figure 1, the latitudinal wind profile at 700 mb. (averaged over 360°), shows no displacement of the westerly maximum from normal. It does, however, suggest strong anticyclonic shear south of the stronger than normal peak values since the westerlies fell to below normal strength at 37.5° N. and the easterlies (at 700 mb.) extended northward to about 28° N. The net effect was an intensification and latitudinal contraction of the subtropical ridge axis, with a mean northward displacement of the ridge axis.

Figure 2, the mean 700-mb. contours and height departures from normal for September, delineates the perturbations associated with the hemispheric wind profile of figure 1. Three major "full"-latitude troughs can be seen, over eastern North America, central Russia, and the central Pacific. The strongest of these was the Russian trough with heights almost 400 ft. below normal. In addition there were 3 secondary troughs: in the eastern Atlantic, eastern Asia, and eastern Pacific. The latter of these existed on the southern periphery of the 700-mb. westerly belt and was directly involved in the zonal westerlies on only a transitory basis. On some occasions it was completely cut off from westerly control.

In many respects this pattern was quite similar to that of August 1956 [1] with, however, many of the features showing westward displacement. A notable exception to this general retrogression was the shear of the eastern Atlantic trough of August as the higher-latitude portion proceeded eastward and deepened in Russia (cf. above and fig. 2). The lower-latitude portion of the trough remained in a position quite similar to that of August and continued the anomalous cyclonic activity at middle latitudes of the eastern Atlantic. In possible connection with this situation, it is of interest to note that the *S. S. Roma* reported a small ice floe near the Azores (41°30′ N., 29° 00′ W.) on September 12—an unusual happening in recent years.

[1] See Charts I-XVII following p. 352 for analyzed climatological data for the month.

2. TEMPERATURES IN THE UNITED STATES

The pattern of a ridge over the western United States and a trough in the East is a common one in summer and fall months. During September an intensified subtropical ridge axis was displaced northward in the West and a stronger than normal trough dominated in the East. These may be readily related to the temperature and precipitation anomalies, particularly because the circulation features were unusually persistent throughout the month.

The observed temperature regime for September (Chart I, A and B) showed that above normal temperatures prevailed over much of the West under above normal heights and anticyclonic circulation at 700 mb. Considerable areas of the Southwest averaged 4° to 6° F. above normal. Numerous daily and late-season maximum temperature records were broken. San Diego had the highest average maximum temperature for any month of record, Burbank had its warmest and sunniest September, and Los Angeles and Tucson had their second warmest Septembers of record.

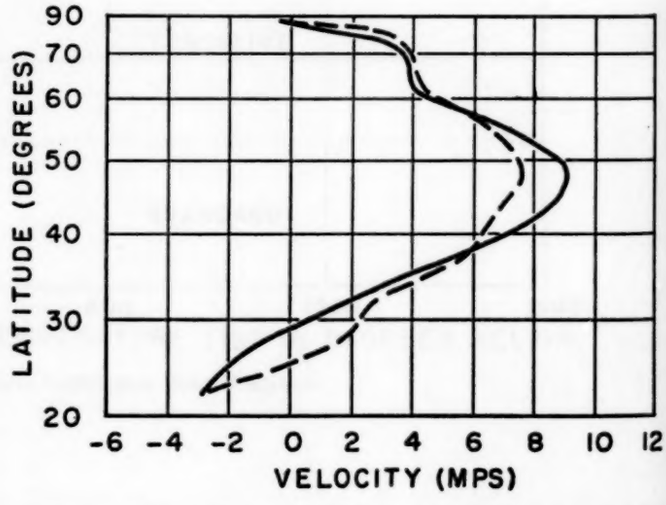

FIGURE 1.—Mean 700-mb. zonal wind-speed profile in meters per second for the Northern Hemisphere (360°) for September 1956 (solid curve) with normal September curve dashed. Note peak westerlies were stronger than normal but not displaced from normal latitude of maximum, although easterlies (negative values) extended farther north than normal.

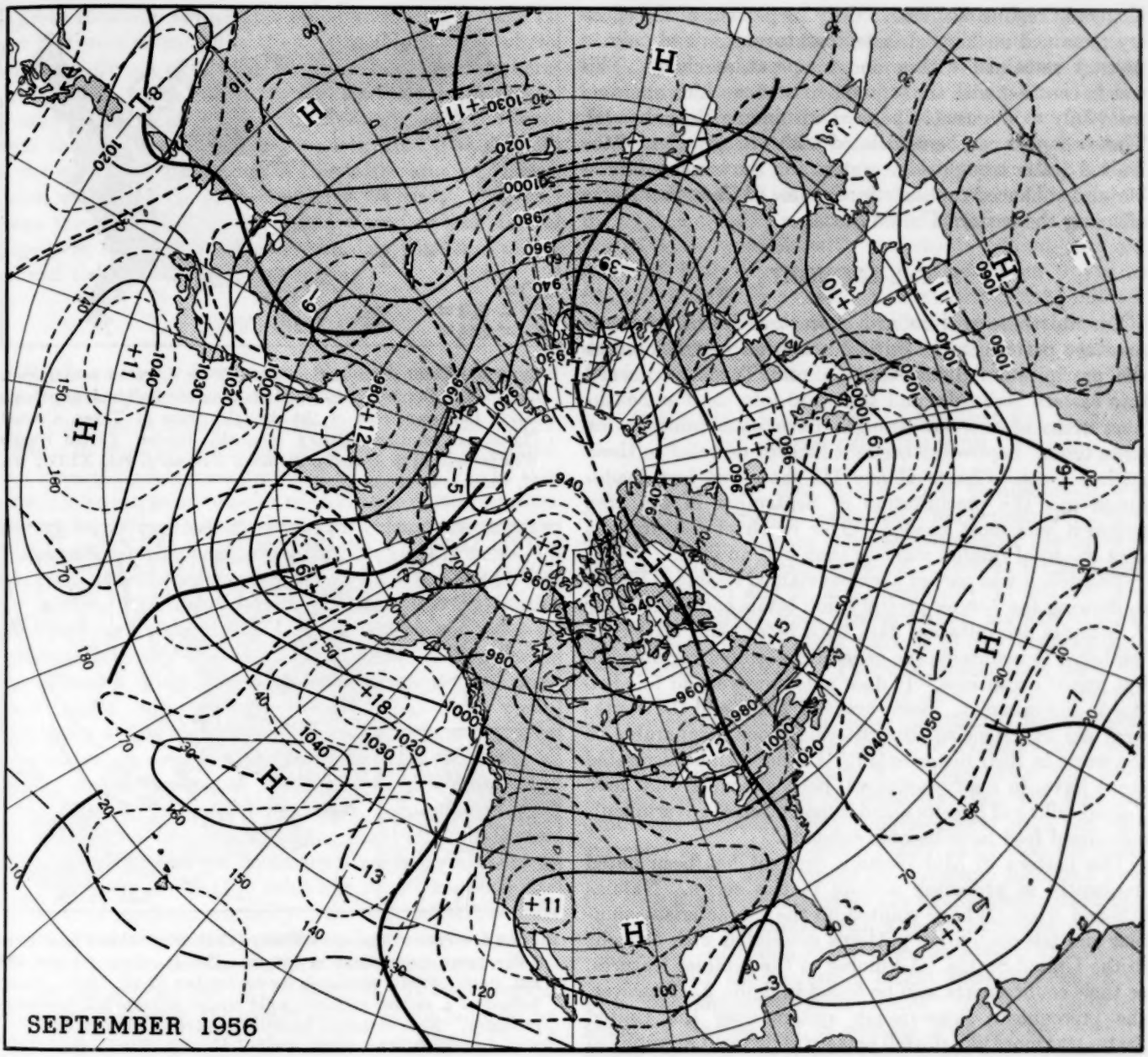

FIGURE 2.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for September 1956. Regional features of note include: strong ridge in western North America, trough in eastern North America, pronounced middle-latitude trough activity (similar to August 1956) in eastern Atlantic, greatest departures (−390 ft.) in Russian trough.

Contrariwise, the East was under the influence of cooler than normal Canadian air. Behind the cyclones (Chart X) passing eastward through southern Canada or northeastward through the Great Lakes, outbreaks of cold Canadian air (Chart IX) swept southeastward into the mean trough. Temperatures averaged 6° F. below normal in parts of Pennsylvania and Ohio and generally below normal everywhere east of the Mississippi Valley. In northern States the departures were relatively extreme as Caribou and Portland, Maine reported their second coldest September; Albany, N. Y., the coldest September in 120 years; Scranton, Pa., its coldest on record, and Boston, Mass., its coldest since 1917.

Scranton, Pa., and Buffalo, N. Y., had their earliest snows on record, and Sault Ste. Marie, Mich., its greatest September snowfall (2.7 in.). One may evidently conclude that the pronounced and persistent ridge-trough configuration combined with colder than normal conditions over the Canadian source region [3] to effect marked deviations from average September weather.

A comparison of the monthly temperatures for August [1] with those for September indicates that a considerable

change in regime occurred. Only 21 percent of the country remained unchanged in temperature class and only 54 percent remained within one temperature class.[2] This was in contrast with the strong persistence which operated from July to August (85 percent within one-class change). These changes can be associated with retrogression of the United States trough-ridge system and the increased number and enhanced cooling effectiveness of Canadian Highs affecting the eastern United States.

3. THE DROUGHT

Despite these well-defined characteristics of the temperature pattern, more critical attention was devoted to the precipitation distribution. From Texas northward into eastern Nebraska and westward into the Far Southwest areas of extreme drought have been common for some time. September brought little or no relief to these critical areas. Charts II and III show just how inadequate was the precipitation of September in the area where it was most needed. Over much of the drought area the total rainfall was less than half an inch.

The deficit was part of a long-sustained regime. Figure 3, showing the 7-week precipitation totals ending October 7, includes precipitation data both before and after September. It maintains the general September regime with but minor exceptions. It does not, however, do full justice to the calamity. Some areas of Texas and the Southwest are experiencing drought conditions comparable to the worst in their histories [13]. Pastures and unirrigated crops have, in many instances, been almost a total loss. Forced selling of livestock and importation of government-subsidized feed have become common.

The pattern of Mid-Western drought has been noted frequently in preceding articles in this series. Namias [12] and Klein [7] have pointed up the characteristic summer and fall circulation patterns associated with drought in the United States. A number of the summer features, or their counterparts, can be found in figure 2. However, the prerequisite ridge-trough system over the United States was more like the fall pattern of drought exemplified by October 1952 [18] or September 1953 [7]. The latter month was similar to this September in a number of respects in addition to the drought regime (e. g., see the date and path of hurricane Florence) but, curiously enough, was quite dissimilar over the eastern Pacific. This may, as Namias [12] has indicated, further substantiate the influence of the Atlantic sector on North American circulations.

From a longer-range point of view, the mid-continent drought area was displaced southward relative to the drought area of the "thirties" when it extended to the Canadian border. Although a completely satisfactory and objective drought index has not yet been developed,

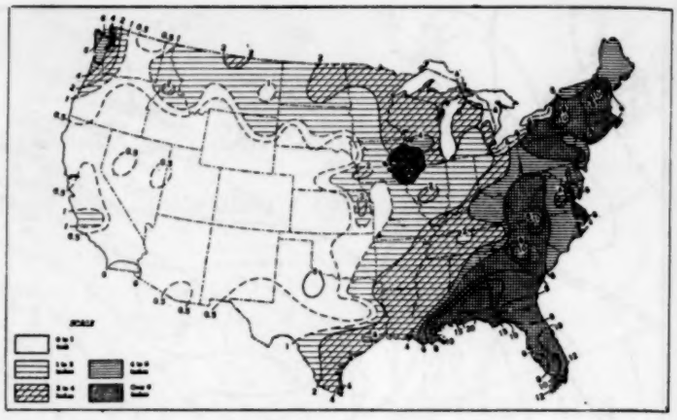

FIGURE 3.—Total precipitation (inches) for 7 weeks ending midnight l. s. t. October 7, 1956. Less than one-half inch of precipitation fell over most of the drought areas of Texas, Central Plains, and southern Rocky Mountain States. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIII, No. 41, October 8, 1956.)

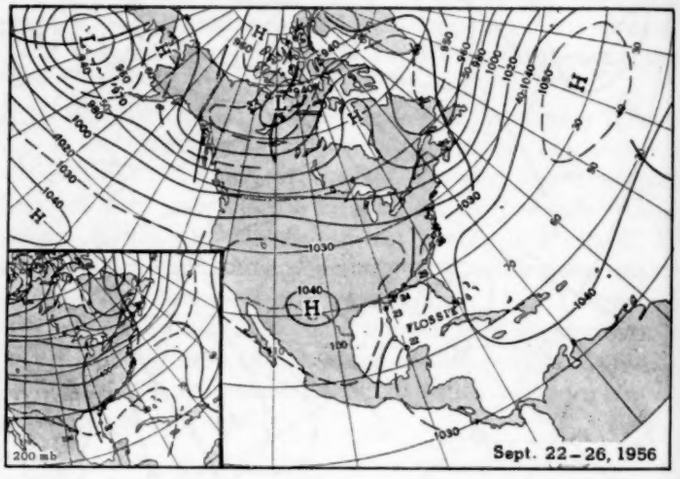

FIGURE 4.—Path of hurricane Flossy (12-hour positions) relative to 5-day mean circulations at 700 mb. (200-ft. contours) and 200 mb. (inset, 400-ft. contours) for September 22–26, 1956. Dates indicate 7 a. m. EST position; solid circles indicate full hurricane intensity. Note eastward tracking relative to 200-mb. flow.

there is general agreement that current conditions in the drought area defined above are the culmination of recurrent moisture deficiencies, particularly during the growing season, over a number of years. Namias [12] has treated summer drought patterns of 1952–54. Palmer [13] compared historic droughts with the current one in western Kansas by means of an experimental index and in [14] shows the extent and severity of drought conditions for the period 1954–56. Thus, over much of this area, the current drought can be traced back through four summers and current hardships are the culmination of a prolonged pattern of moisture deficiency. The basic reasons for such phenomena are still unexplained. However, with the growth of knowledge in the physical sciences, new concentration on this specific problem may lead to a general solution which will permit the forecasting of these regimes.

[2] Monthly temperature classes are defined with reference to the monthly variability and normal temperature for each station. Limiting departures are determined from past records so that the classes below, near, and above normal each occur ¼ of the time, while much below and much above occur ⅙ of the time.

Areas receiving appreciable precipitation (cf. Charts II and III) were restricted to the extreme Northwest, where the mean trough effected a limited rainfall; the northern Great Lakes, which was influenced by the passage of migratory cyclones into the nearby trough; and the area from the western Appalachians eastward. The rainfall in the northernmost portion of this latter area was associated with typical cyclonic activity associated with the mean trough. That in the southern portion was due in large part to hurricane Flossy, the only hurricane which entered the United States this season.

4. HURRICANE FLOSSY

Hurricane Flossy first became a closed circulation over the Yucatan peninsula on September 21 [16]. Its formation might be profitably investigated in detail in a later study. In gross aspect initial deepening might be related to a circulation sequence proposed by Riehl [15]. In this sequence an intrusion of polar westerlies or northwesterlies (at high levels) into lower latitudes provides the divergence mechanism which deepens a preexisting disturbance, in this case, a westward-moving easterly wave. The closed low center, once formed over Yucatan, moved north-northwestward through the Gulf of Mexico and reached hurricane intensity on the 23d, southwest of Burrwood, La. Flossy's track, including its subsequent northeastward motion, together with the attendant 5-day mean circulation at 700 and 200 mb., is shown in figure 4. The sheared trough over eastern North America (both levels) for the period September 22–26 had been a continuous trough during the preceding period, September 18–22. Northwesterlies to the rear of the lower-latitude trough presumably supplied the necessary divergence mechanism [15]. At lower levels (700 mb.) one might associate the injection of cyclonic vorticity from the westerlies into lower latitudes with the preexisting Low sought by Bergeron [2]; i. e., the mechanism for organizing the convective circulations as described by Namias [10]. It seems logical to assume that since the trough shear was not followed by rapid anticyclogenesis at higher levels over central United States latitudes, the continued presence of westerlies aloft influenced the strong eastward component of motion which prevailed as the storm emerged from the Gulf.

At the 700-mb. level the direct trace of the storm in the contour field was clearly evident, but reason for the strong eastward steering could be found in the westerlies at 200 mb. (fig. 4, inset). The track could also be related to the monthly mean 700-mb. pattern (fig. 2).

In typical fashion, Flossy lost its hurricane winds shortly after moving inland and became extratropical in character at a relatively early stage over Georgia.[3] Highest winds were estimated 90 to 110 m. p. h. at Burrwood, La. and 64 m. p. h. at Pensacola, Fla., decreasing farther northward. Motion was quite slow, particularly after the storm acquired extratropical form. This deceleration was, in part at least, associated with southeastward motion of the ridge over Canada (fig. 4) and subsequent blocking of the storm. As a result of the slow motion, precipitation was fairly heavy over wide areas of the Southeast. Total storm rainfall amounted to 7.05 in. at Burrwood and 10.69 in. at Pensacola. It decreased farther northward to 7.09 in. at Mobile, Ala., 4.4 in. at Columbia, S. C., 3.42 in. at Hatteras, N. C., and 1.50 in. at Richmond, Va. A number of tornadoes were reported in connection with the storm. Total damage, much of it due to flooding and wind-driven waves at coastal installations, was estimated at $12 million. Apart from its violent aspects, Flossy greatly relieved the droughty conditions which had prevailed in northern Florida, Georgia, and the Carolinas.

[3] For a detailed discussion of this transition see adjacent article by Richter and DiLoreto

5. TYPHOONS AND TROPICAL STORMS RELATED TO MEAN CIRCULATION

If one assumes that strong, deep (latitudinally and vertically), subtropical easterlies often accompany hurricane development, then this past September should have been a prolific hurricane spawner. Both at sea level and 700 mb. (figs. 1 and 2), and presumably, at 500 mb., the Atlantic easterlies were stronger than normal. In all, four tropical storms were tracked in the Gulf-Atlantic area during September. This was greater than the usual frequency of occurrence. Only one, Flossy, reached hurricane strength and at least one (Ethel) lacked rigorous substantiating data of sustained existence over considerable time (see Chart X). Apparently the gross pattern was favorable to initiation, but the sensitive conditions necessary for full development were not concurrently at hand. It seems highly likely that the mean circulation was unfavorable for hurricane incidence over the New England States since the strong westerlies almost precluded the possibility of an Atlantic hurricane reaching that area. Although figure 2 shows several features in common with the pattern of height anomalies associated with "maximum hurricane threat" (to New England) found by Namias [11], it notably lacks the key positive height anomaly over central Canada and is quite dissimilar over the Pacific and eastern Atlantic. It is intriguing that the only hurricane type (Gulf) which might have had the capability of reaching the northeastern seaboard almost did just that, as Flossy managed to produce some gusty winds and moderate rain as far north as southern New England. This may be compared to hurricane Betsy of August 1956 [1].

In contrast to the dearth of full hurricane activity in the Caribbean was the series of typhoons which occupied the western Pacific during September. Including typhoon Dinah, in progress as the month began, and the short-lived Ivy, there were 6 typhoons of full hurricane intensity in September—a significant increase over the 3 or 4 storms which normally approach typhoon intensity during this month [4]. Half of these typhoons did not recurve but crossed the coastline into the continent of

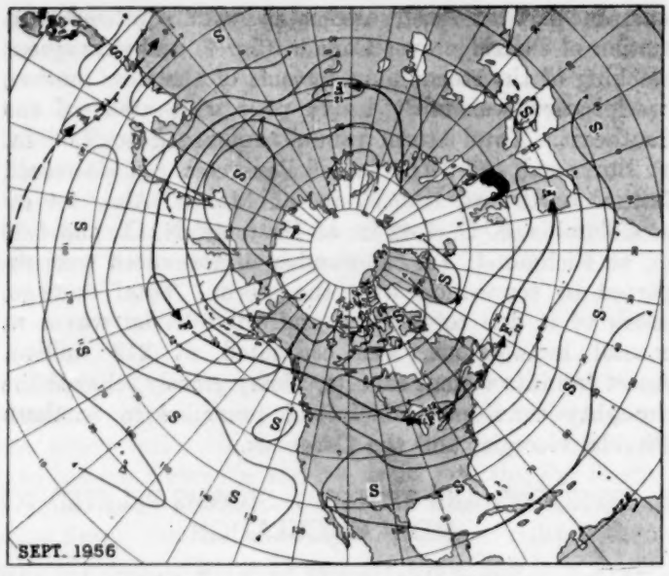

FIGURE 5.—Mean 700-mb. isotachs (labeled in meters per second) for September 1956. Axes of westerly maxima indicated by solid, easterly by dashed, arrows. 700-mb. easterlies were quite strong in tropical western Pacific but data coverage was not adequate to show strength and location of Atlantic easterly maximum.

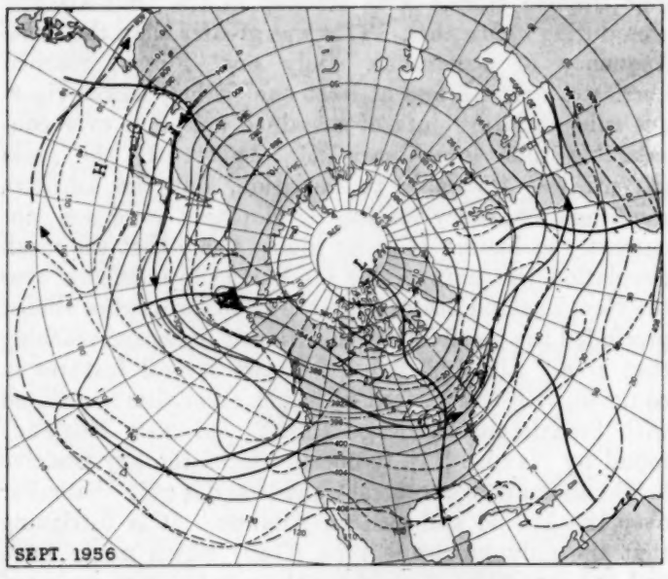

FIGURE 6.—Mean 200-mb. contours (in hundreds of feet) and isotachs (in meters per second) for September 1956. Solid arrows show westerly jet was fairly far south and strong over eastern North America. Easterly maximum (dashed) extended quite strongly to 200 mb. in western Pacific.

Asia. This percentage was not unusual, but the latitudes at which the storms entered the China coast were farther north than usual; i. e., Formosa rather than Hainan [4].

Mean conditions over the western Pacific were, a priori, (as in the Atlantic) favorable to tropical storm development. At 700 mb. (fig. 5) the easterlies were stronger than normal, as was the subtropical ridge. The latter was also farther north as well as stronger than normal. Both of these factors may be related to the higher frequency of unrecurved storms at Formosa and the westward displacement (from normal) of the locus of typhoon activity. The mean 200-mb. pattern, figure 6, shows the subtropical ridge extending east-northeastward from just north of Formosa. An east wind maximum was observed (dashed arrow, fig. 6) south of the ridge, a regime quite different from that which prevailed over the western Atlantic.

Figure 7 shows the tracks of the 5 major typhoons of September in chronological order, together with the appropriate 5-day mean 700-mb. and local 200-mb. circulation patterns. In general, one might expect this type of activity, given the monthly circulations (figs. 2, 6). Comparisons may be made with similar data relating tropical storms to mean circulation [1, 5, 7, 10, 11, 19]. However, it should be of some further interest to examine the differences in circulation patterns attending recurvature as opposed to the cases of no recurvature. Since mean maps over Asia are not available at 200 mb., most of the circulation characteristics must be discussed in terms of the 700-mb. features. In general, the main westerly circulation features are similar, but by no means identical at the two levels.

A. TYPHOONS NOT UNDERGOING RECURVATURE

Typhoon Dinah, figure 7A, roughly illustrates the classical pattern in which recurvature is improbable. The long-wave trough over Siberia was almost a half wavelength upstream from the tropical cyclonic activity. The resulting difference in phase between high- and low-latitude systems operated to strengthen the ridge north of the typhoon and to prevent recurvature before the storm was driven ashore and dissipated. At 200 mb. the strong zonal ridge with upper-level easterlies to its south exerted a similar influence.

Typhoon Freda, figure 7C, followed a path almost identical to that of Dinah. However, it is quite evident that there was a westerly trough to the north of the tropical disturbance and the main question might be: why did the typhoon not recurve? This question is particularly apt in view of the high latitude of the storm path. The answer appears to be in the flat, fast, westerly flow across Siberia which occurred downstream from a confluence regime over European Russia. The subtropical ridge is maintained reasonably well to the south of such flows and was strongly in evidence at the 200-mb. level (fig. 7C, inset). In the last analysis, the breaking of the subtropical ridge axis in borderline situations may depend on the timing of the westerly trough to the north relative to the normal approach of the tropical storm to the ridge axis. In any case, the effectiveness of a given trough in breaking the subtropical ridge is determined by the amplitude and location of the upstream trough-ridge system [6, 8, 9, 17].

The general situation was very similar for typhoon

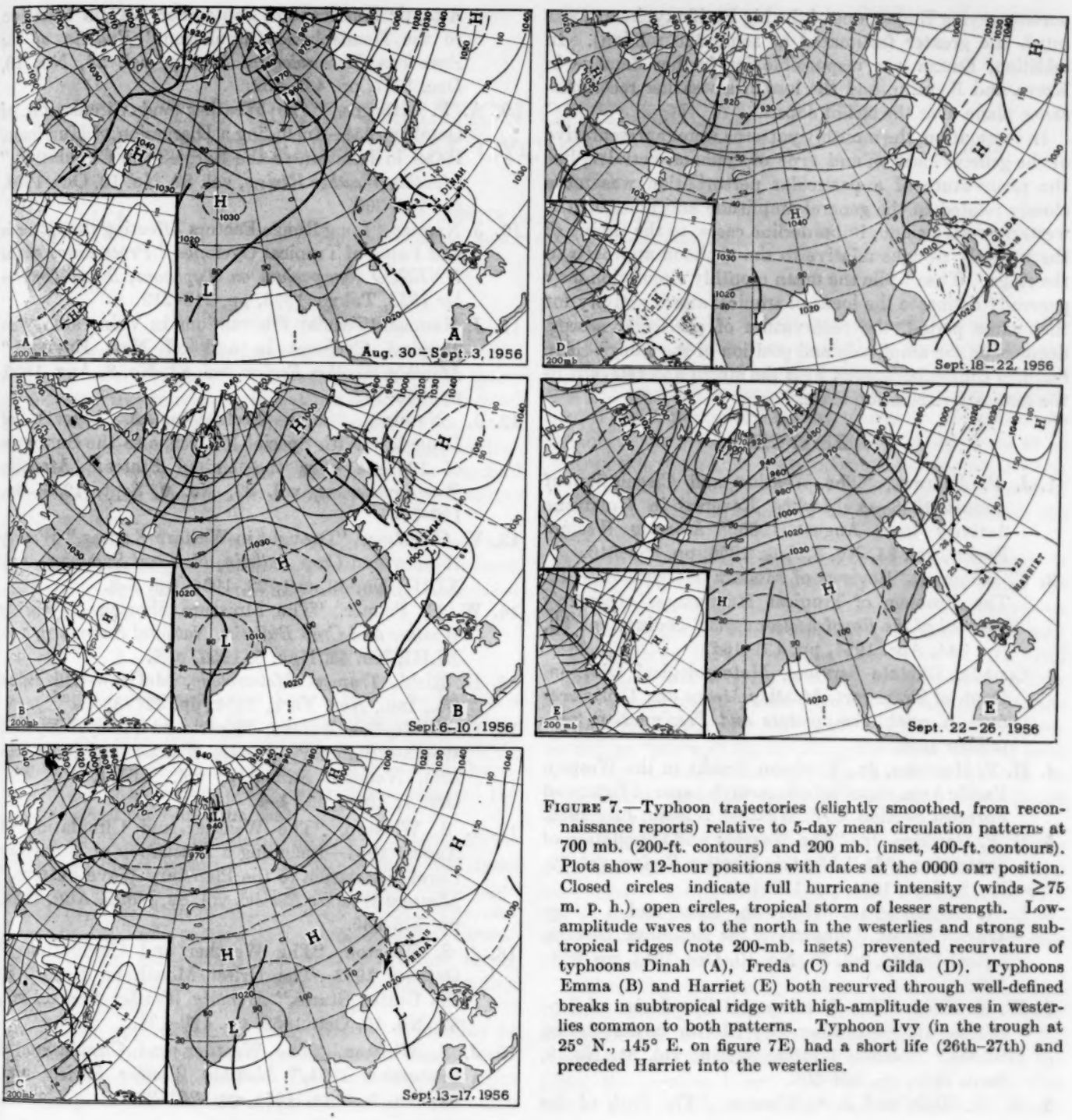

FIGURE 7.—Typhoon trajectories (slightly smoothed, from reconnaissance reports) relative to 5-day mean circulation patterns at 700 mb. (200-ft. contours) and 200 mb. (inset, 400-ft. contours). Plots show 12-hour positions with dates at the 0000 GMT position. Closed circles indicate full hurricane intensity (winds ≥75 m. p. h.), open circles, tropical storm of lesser strength. Low-amplitude waves to the north in the westerlies and strong subtropical ridges (note 200-mb. insets) prevented recurvature of typhoons Dinah (A), Freda (C) and Gilda (D). Typhoons Emma (B) and Harriet (E) both recurved through well-defined breaks in subtropical ridge with high-amplitude waves in westerlies common to both patterns. Typhoon Ivy (in the trough at 25° N., 145° E. on figure 7E) had a short life (26th–27th) and preceded Harriet into the westerlies.

Gilda, figure 7D, which originated some 8° farther south than Freda. It, similarly, could not break through the subtropical ridge primarily because of the strength of the ridge axis (note fig. 7D, inset) and the low amplitude of the westerly perturbations to the north.

B. RECURVING TYPHOONS

The foregoing may be contrasted with the typhoons which recurved: Emma, figure 7B, and Harriet, figure 7E. In these cases, at both 700 and 200 mb., wave amplitudes were greater both locally and upstream. The 200-mb. ridge was weakened or completely broken through as 200-mb. steering appeared operative. From the data currently available, it appears that the 200-mb. ridge line gave better indication of both the break-through and the latitude of recurvature than did the 700-mb. level, which reflected quite strongly the storm circulation itself. While both Emma and Harriet struck Okinawa, the destruction

accompanying Emma, one of the big Pacific typhoons, was much the greater (estimated at some $20 million). In addition, Emma was responsible for further damage in Korea and Kyushu, and the loss of a weather reconnaissance plane over the sea of Japan.

In summation, the monthly patterns were representative of the general location and type of typhoon activity, but the recurvature of a particular perturbation was more closely related to the general amplitude and phase of the westerly systems and, in borderline cases, to the timing of the westerly troughs relative to the typhoon approach to the ridge. Thus while the mean monthly circulation may generally delineate the locus of tropical storm activity for that same period, the recurvature of particular storms depends on the amplitude and position of the trough-ridge features contemporaneous with the storm and relevant to the monthly circulation state.

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THE TRANSFORMATION OF HURRICANE FLOSSY INTO AN EXTRATROPICAL CYCLONE, SEPTEMBER 25–29, 1956

D. A. RICHTER and E. A. DILORETO
National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

Flossy was the first hurricane of the season to enter the United States. While it is interesting to study this storm as a destructive hurricane, this paper is intended instead to show its transformation from a tropical to an extratropical cyclone, its retardation by a building surface anticyclone over southeastern Canada, and its eventual filling and more rapid movement northeastward over the Atlantic Ocean.

Some special attention is given to the explanations and theories concerning the sharp curvature of Flossy's track and the orographical precipitation directly associated with the storm.

2. ANTECEDENT CONDITIONS

A tropical depression was first detected as having a definite circulation over the Yucatan Peninsula on September 21, 1956 [13]. The storm moved north-northwestward across the Gulf of Mexico and reached hurricane intensity on September 23, when it was centered 125 miles south of the Louisiana coast.

Meanwhile, a low pressure system was moving across the Great Lakes region (not shown) with a cold front extending southwestward through the middle Mississippi Valley and the South-Central Plains region. The corresponding 500-mb. pattern on September 23 (not shown) accompanying the surface Low had a cyclonic center located near The Pas, Manitoba, with a trough extending southward through Minnesota and Iowa.

As Flossy approached the Gulf Coast on September 24 (fig. 1A), the Great Lakes low pressure center moved eastsoutheastward to eastern New York with the cold front advancing to the eastern Appalachians and extending southward to northern Alabama. The associated 500-mb. trough (fig. 1B) extended southward over the Ohio Valley. The corresponding 1,000–500-mb. thickness chart (fig. 1C) shows negative departures from normal of 200–400 feet following the front.

3. RECURVATURE

It can be seen from figure 1C that, in the southeastern United States, thickness values were below normal to the north of 29° N. and above normal over the Gulf of Mexico to the south. As Flossy approached Louisiana, the juxtaposition of the pure tropical air accompanying the hurricane and the cool modified air to the north caused the thermal gradient to increase, thereby making a stronger barrier for a northward-moving storm to penetrate. As the hurricane was not of such severe proportions as to destroy this thermal field and continue moving northward, it both made an almost 90° turn to the right just north of Burrwood, La., and began to fill soon after crossing the shoreline.

Not to be overlooked as a possible contributing factor to Flossy's recurvature is the frictional effect. Since the angular deviation of the wind from the isobar increases with the roughness of the underlying surface (Petterssen [9]), it follows that as the hurricane neared the Gulf Coast there was a great amount of cross-isobaric flow caused by increased friction due to air flowing over the rougher land from over the water. This convergent zone tended to "pile up" the air along the coast, thus at least retarding its northward movement. It is difficult to contemplate quantitatively just how much this affected the actual veering.

Examination of the 700–500-mb. mean temperatures (not shown) makes it readily evident that the sharp curvature of the hurricane to the right was in accord with the warm tongue steering principle (Simpson [11]). However, the degree of curvature of this particular storm was slightly more than this steering method indicated.

Still another forecasting tool used to some extent is a method offered by Cline [5] which moves a hurricane along an axis of maximum precipitation intensity. He concluded that in tropical cyclones which curved to the right, the greatest hourly rainfall intensity was farther to the right of the line along which the cyclonic center was advancing at the time. Although we had but limited reporting stations along the coast, it appears that the maximum precipitation was to the right of an instantaneous track of the moving hurricane (fig. 9). After recurvature, Flossy moved approximately in a straight line toward the region of the greatest precipitation intensity (fig. 10).

4. RETARDATION

As the 500-mb. trough that was associated with the

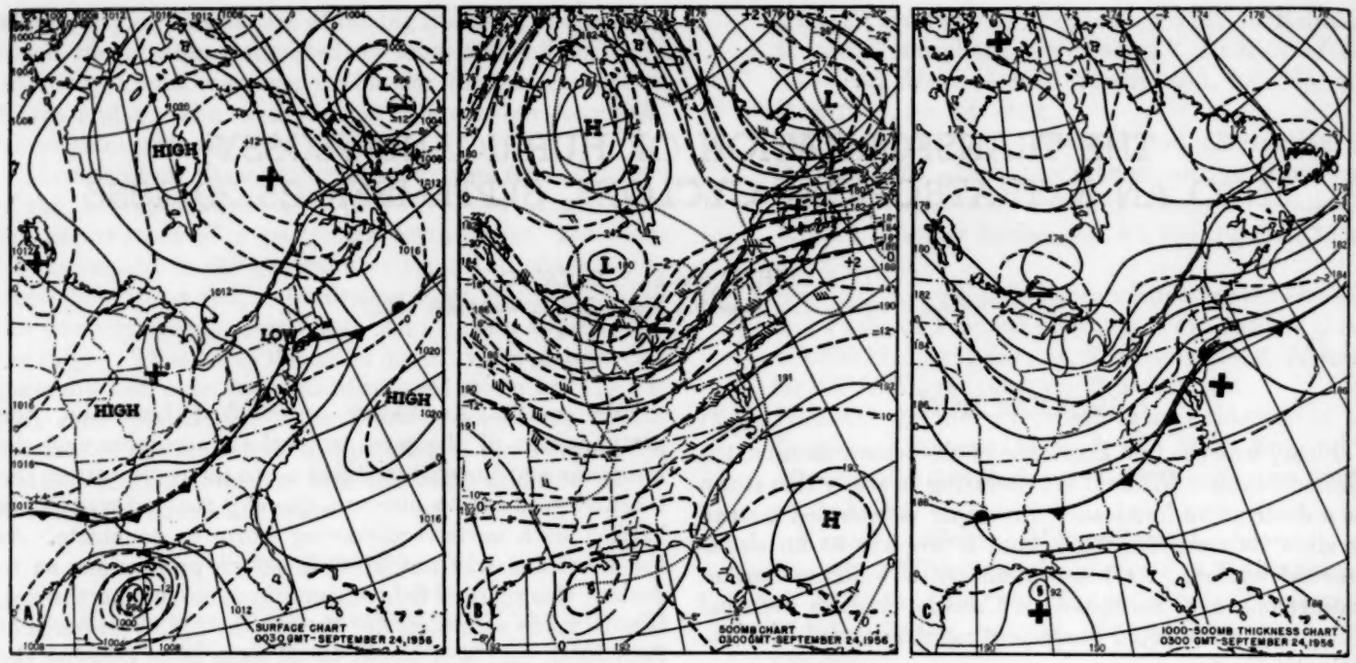

FIGURE 1.—September 24, 1956. (A) Surface chart for 0030 GMT, with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT. Contours (solid lines) are labeled in hundreds of geopotential feet. Superimposed are the 500-mb. 12-hour height changes (dotted lines) in hundreds of feet. (C) 1000–500-mb. thickness chart for 0300 GMT. Thickness (solid lines labeled in hundreds of feet) is proportional to mean virtual temperature. Superimposed are the 1000–500-mb. departures from normal (dashed lines).

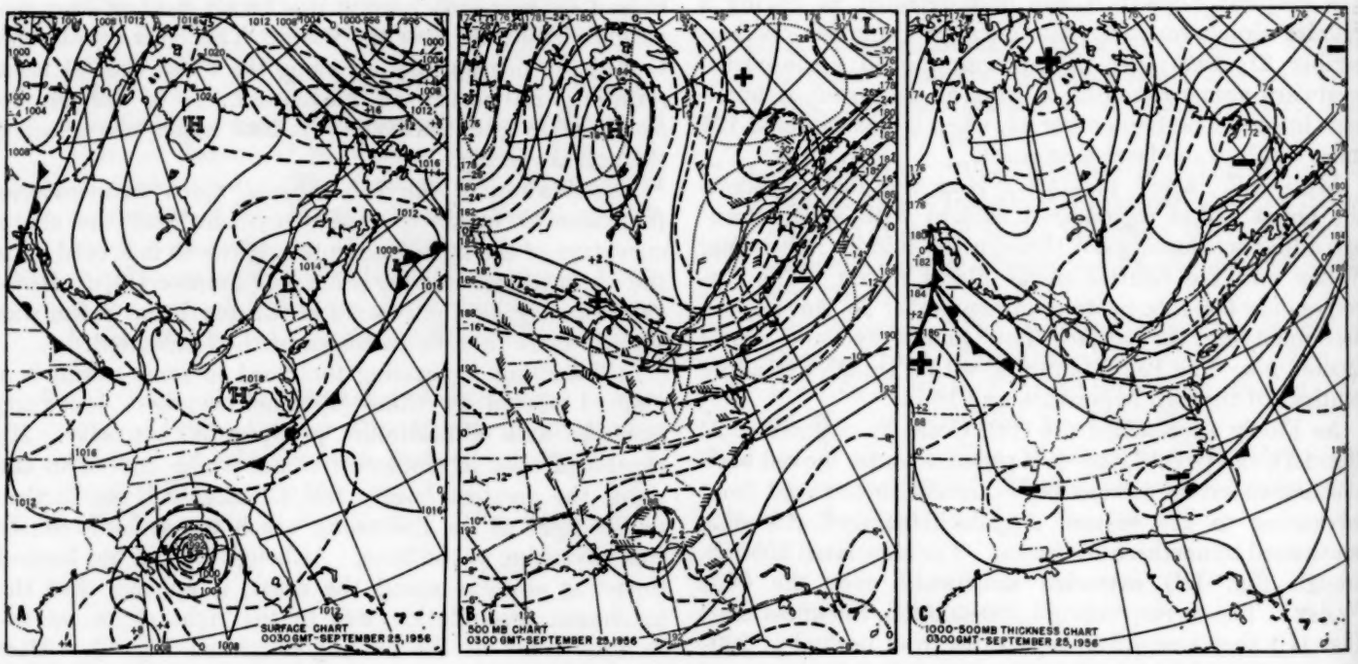

FIGURE 2.—September 25, 1956. (A) Surface chart for 0030 GMT with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

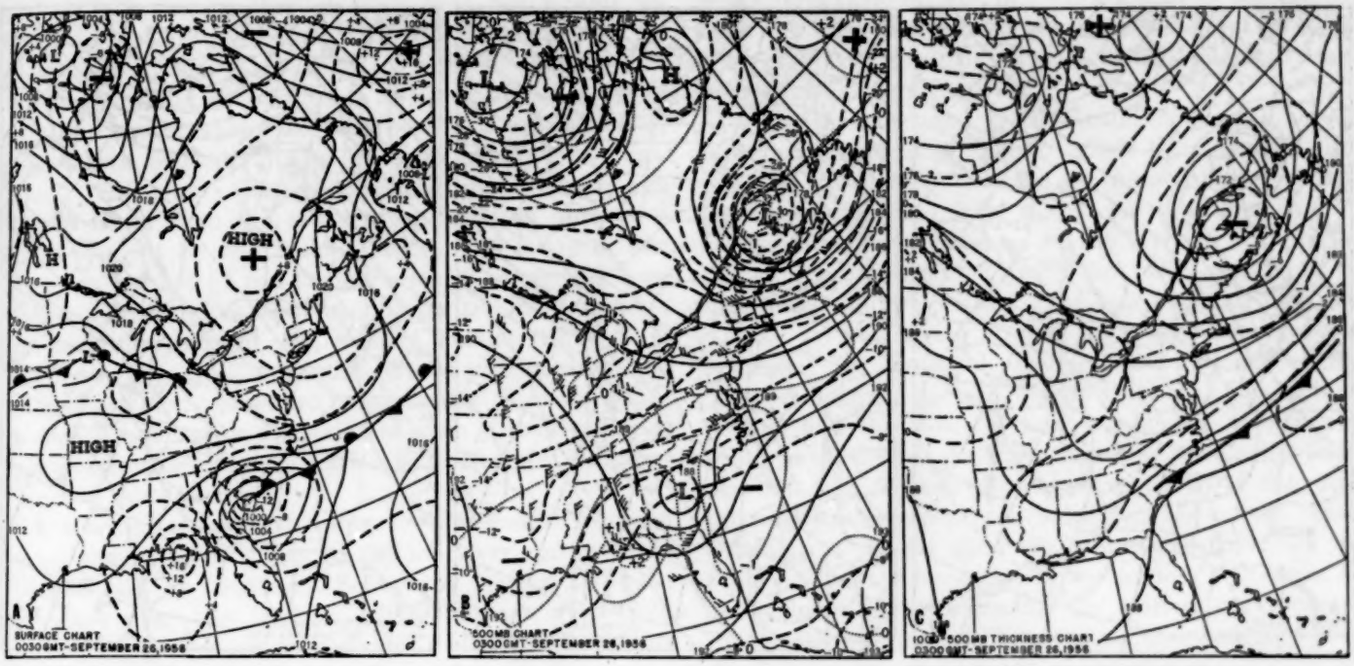

FIGURE 3.—September 26, 1956. (A) Surface chart for 0030 GMT with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

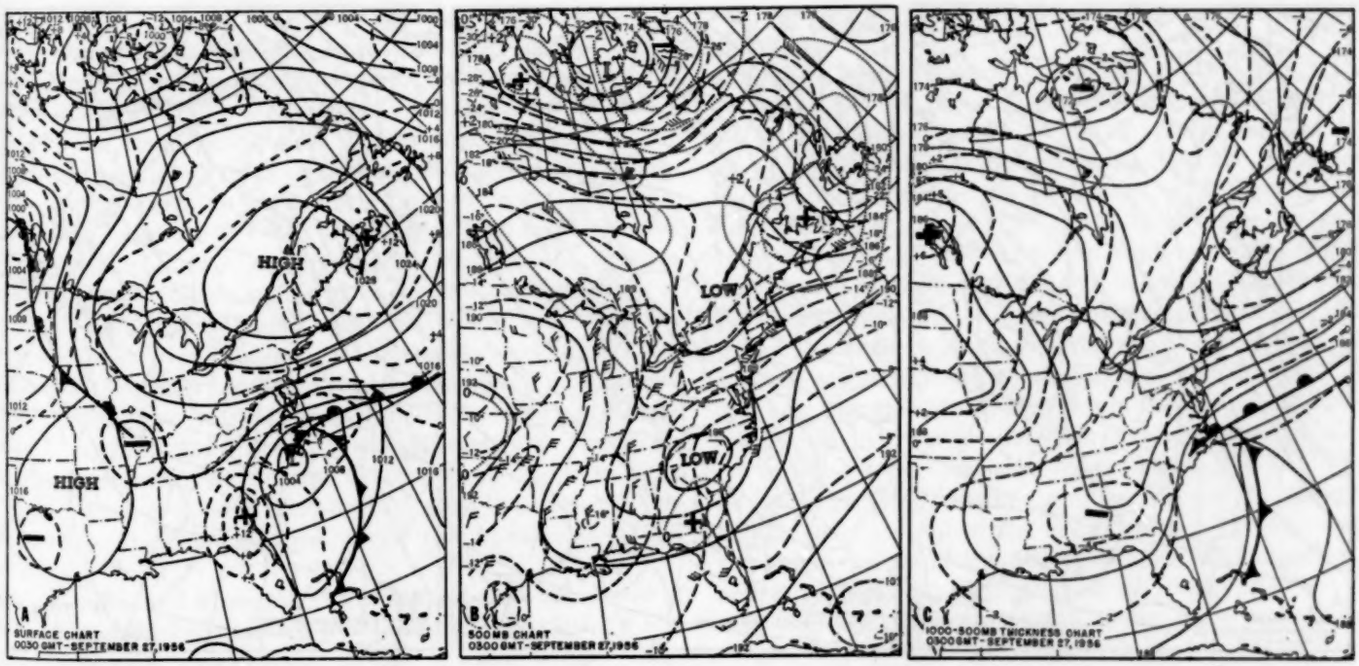

FIGURE 4.—September 27, 1956. (A) Surface chart for 0030 GMT, with corresponding 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT, with superimposed 1000–500-mb. thickness departures from normal (dashed lines).

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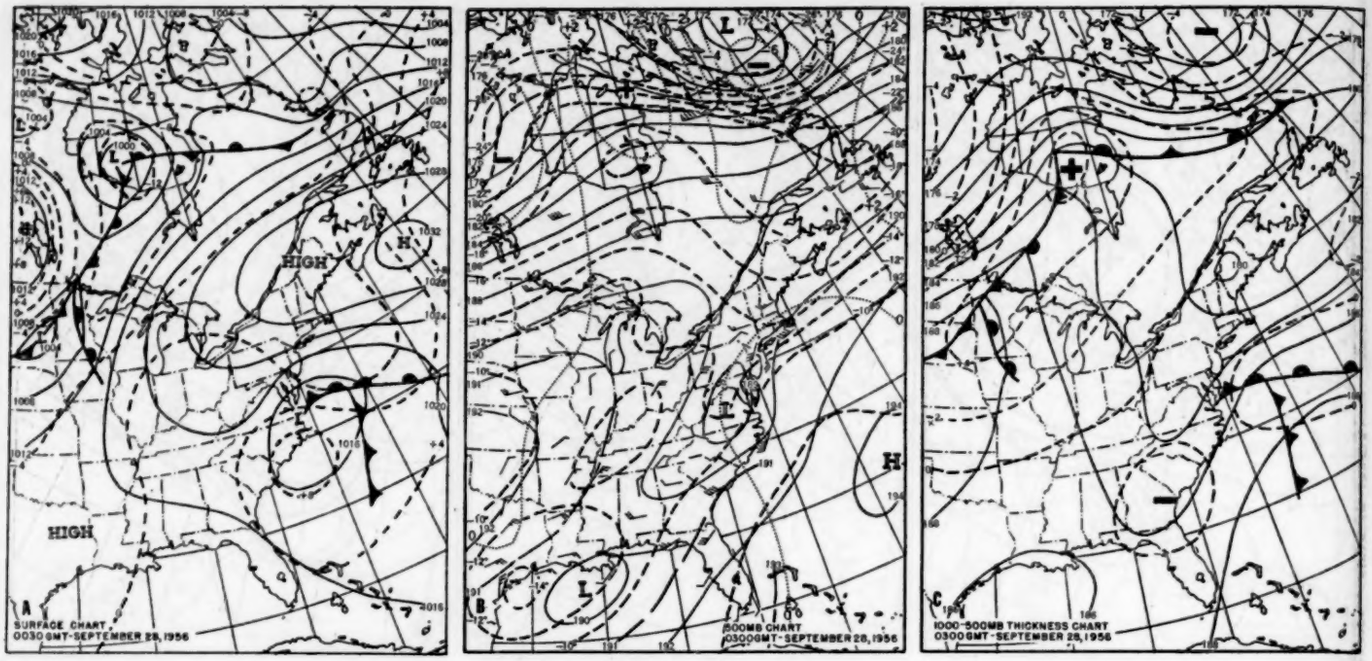

FIGURE 5.—September 28, 1956. (A) Surface map for 0030 GMT, with 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with corresponding 12-hour 500-mb. height change (dotted lines). (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

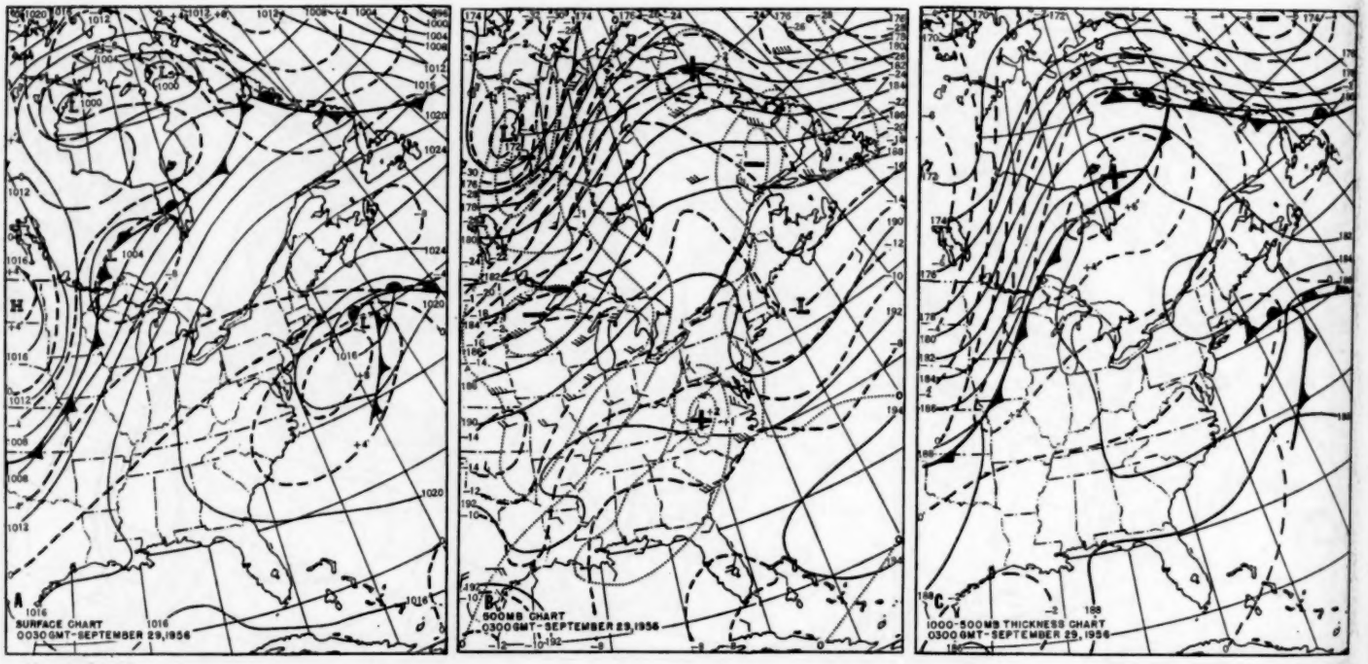

FIGURE 6.—September 29, 1956. (A) Surface chart for 0030 GMT, with associated 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height change (dotted lines) overlaid. (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

surface Low moving through New York State came directly in a north-south line with the trough formed by Flossy, it was thought possible by some forecasters that the storm would get caught in the westerlies (cf. Riehl [10]) and move rapidly northeastward. Examination of consecutive 500-mb. charts of September 24–26 (figs. 1B, 2B, 3B) shows that the northern part of the trough moved faster than the southern, giving it a northeast-southwest tilt by the 26th. Height rises following the northern section of the trough bridged across the New England States, thus disconnecting the tropical Low from the zonal flow pattern and, in effect, cutting it off.

The southern trough then decelerated with an associated retardation of the eastward component of Flossy's movement. A qualitative discussion of some of the dynamical factors effecting this deceleration will be helpful in understanding this occurrence.

A thermal trough extending southwestward from an easterly-moving low center at 500 mb. over northwestern Canada had by 0300 GMT, September 25 (fig. 2B) been advected over the Dakotas. The difluent wind field (Bjerknes [3]) over this area effected a slight cross-contour flow southward so that 24 hours later, 0300 GMT September 26 (fig. 3B), a pronounced thermal trough extended from the Great Lakes area to southeastern Colorado. The corresponding 1000–500-mb. thickness chart (fig. 3C) indicated a thermal ridge in this position. Inspection of the 1000–700-mb. thickness chart (not shown) for the same time shows an even more pronounced thermal ridge. However, a 700–500-mb. thickness field (not shown), derived by graphical subtraction, was found to have a thermal trough in a position that compared favorably with the temperature field at 500 mb. It can then be concluded that all the cooling took place above the 700-mb. level with warming in the lower layers.

On September 27 (fig. 4B), the advection of thermal vorticity from the northwest, together with the absence of any anticyclonic vorticity in the contour field west of the trough, induced small 500-mb. height falls over the lower Mississippi Valley. At the same time the surface isobaric features prevented the southeastward propagation of the low-level warm tongue while the cold air at 500 mb. had nothing to obstruct its southeastward transport. This occurrence allowed the thermal trough aloft to come into phase with and reinforce the already-existing 1000–500-mb. thickness cold trough of the Appalachians (fig. 4C).

Sutcliffe and Forsdyke [12] point out that the center of surface vorticity tends to develop in the direction of and with a speed proportional to the thermal wind. They mention that the area just ahead of the thermal trough line is favorable for cyclogenesis with anticyclogenesis favored to the rear. The advection of thermal vorticity from the west served in this case to retard the 1000–500-mb. thermal trough. Figure 4C shows a general broadening of the southern portion of the trough, actually shifting the mean position westward. The subsequent two thickness charts (figs. 5C and 6C) show a split in the thermal field. A cold pool moved southwestward out over the Gulf of Mexico and the thermal trough associated with Flossy drifted northeastward.

While these events were transpiring in the middle latitudes, a blocking 500-mb. High over Hudson Bay (fig. 1B) was moving eastward as strong cyclonic vorticity advection emanated from a Low north of Fort Nelson. Horizontal mass-divergence in the forward half of this difluent trough resulted from the maintenance of the maximum wind velocities to the rear of the trough line. The air parcels moving through the trough were therefore subjected to continual deceleration and hence were directed outward toward higher heights. This difluent process had the effect of lowering heights considerably faster to the rear of the High than they were rising to the east of it (figs. 2B and 3B) and consequently of elongating the ridge and weakening it slightly. This in turn caused the ridge to become dynamically unstable (Bjerknes [4]); that is, when the curvature in the contour pattern of the anticyclonic flow approached the critical curvature for the strength of the gradient, the air was unable to make the sharp curve over the top of the crest of the ridge and was therefore compelled to cross contours toward lower heights (Wobus [14]). The development of over-shooting supergradient winds on the downstream side of the ridge resulted in the formation and advanced position of a new ridge north of Laborador (fig. 3B), and consequently in the veering of winds in that area to a northeasterly direction.

Further examination of the overall picture shows that on September 24 (fig. 1A), a cold Low moved eastward off the Laborador coast. While the main centers both at the surface (fig. 2A) and aloft (fig. 2B) proceeded uneventfully eastward, a pocket of cold air remained behind at upper levels near Goose Bay, Labrador. The 1000–500-mb. thickness chart on September 25 (fig. 2C) shows values greater than 600 feet below normal. During the next 24 hours, the aforementioned 500-mb. ridge advancing with its northeasterly winds transported this cold air southwestward to the Gulf of St. Lawrence (fig. 3B). In this area the 1000–500-mb. thickness on September 26 (fig. 3C) was greater than 800 feet below normal.

Continued southeastward movement of the ridge and its accompanying warm air advection forced the cold trough eastward out of the coastal area. Comparison of the height values of the 500-mb. charts of September 26 and September 27 (figs. 3B and 4B) with those of the 1000–500-mb. thickness charts of the same period (figs. 3C and 4C) in the Nova Scotia area, shows that while the thickness change was only plus 250 feet, the 500-mb. height change was plus 550 feet, a difference of 300 feet. This 300-foot addition to the 500-mb. height was revealed in a 12-mb. rise in surface pressure (fig. 4A) over Nova Scotia. Similarly comparison of the same sets of charts with corresponding changes in these charts shows that in the area north of New England a plus 150-foot difference

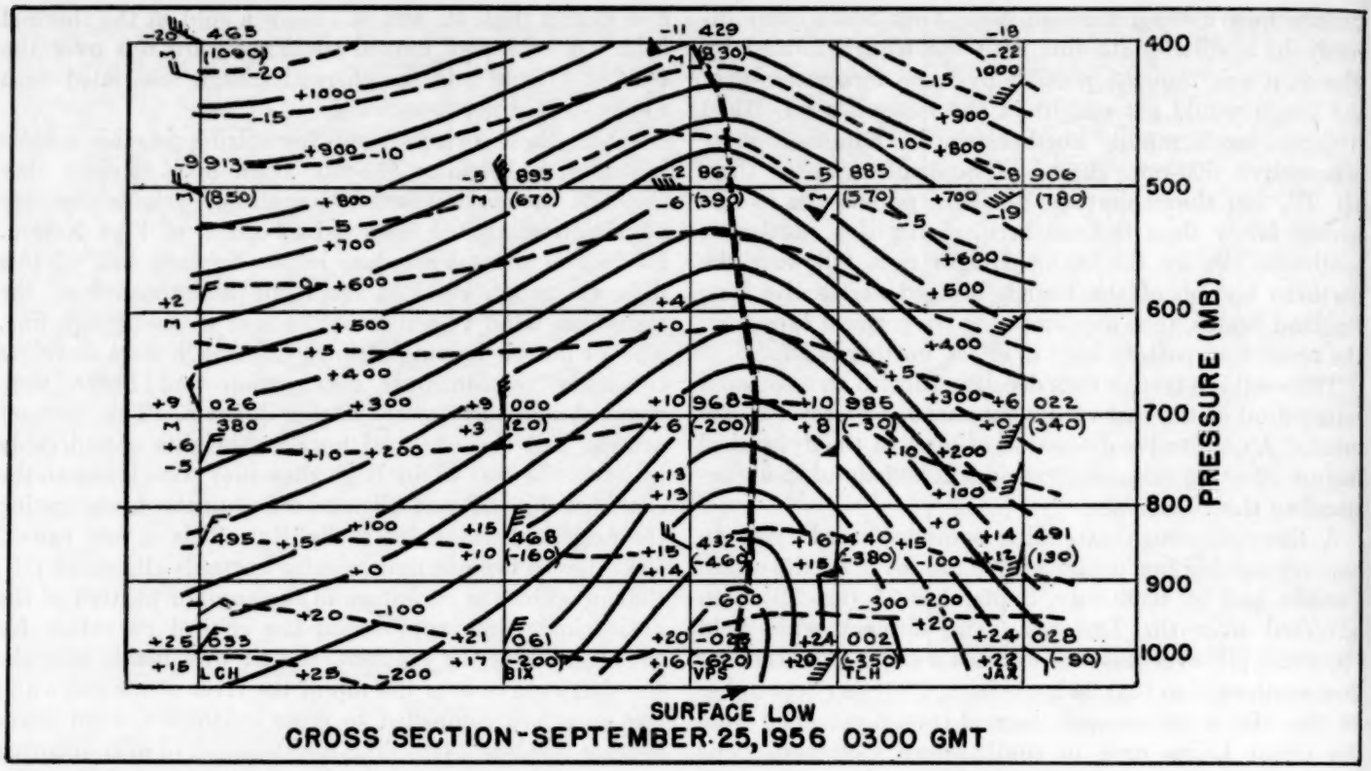

FIGURE 7.—Vertical cross section through center of hurricane on September 25, 1956, 0300 GMT. Figures in parentheses are departure from standard atmosphere using as the standard base: 1000 mb. = 370 ft., 850 mb. = 4, 780 ft., 700 mb. = 9,880 ft., 500 mb. = 18,280 ft., and 400 mb. = 23,560 ft. D-factor isolines (departures from standard atmosphere) are indicated in hundreds of feet (solid lines). Isotherms (dashed lines) are for intervals of 5° C. Heavy dashed line shows the center of the core axis. LCH = Lake Charles, La., BIX = Biloxi, Miss., VPS = Valparaiso, Fla., TLH = Tallahassee, Fla., and JAX = Jacksonville, Fla.

between the thickness and 500-mb. charts existed. This was directly related to a 7-mb. increase in the intensity of the surface High.

The most significant result of the previously discussed synoptic conditions was the development of strong low-level easterly winds along the Mid-Atlantic States. The surface charts of September 24–27 (figs. 1A, 2A, 3A, and 4A) show that the zero isallobar of the 24-hour pressure changes was practically stationary over the State of Virginia throughout this entire period. During that same 72-hour interval, the pressure at Albany, N. Y. rose from 1010 mb. to 1028 mb., while at Wilmington, N. C., as the surface Low moved northeastward, pressures fell from 1017 mb. to 1000 mb. Hence, in view of this 35-mb. increase in gradient and pressure rises to the north, it became very unfavorable for the storm located near the North Carolina coast to advance rapidly in any northerly direction.

On the following day, September 28, the temporarily blocking surface High causing this stagnation was beginning to weaken. A surface Low located near Lake Winnipeg on September 27 and moving northeastward to Hudson Bay on September 28 (fig. 5A) caused strong warm air advection in the northwestern quadrant of the High. A plus 600-ft. 1000–500-mb. thickness departure from normal (fig. 5C) was progressing just in advance of the surface Low. At 500 mb. (fig. 5B), height rises associated with the ridge over the eastern part of Hudson Bay were of much less magnitude than the thickness rises. The effects of this difference were reflected at the surface as pressure falls. Figure 5A also shows that a separate high center had formed east of Nova Scotia in the same general area where, on the previous day, there was a 12-mb. anallobar. The subsequent map (fig. 6A) shows that this became the dominant high center, as the one to its west fell victim to the pressure falls from the northwest and diminished in intensity.

At the same time the remnant of Flossy, while steadily losing strength in central intensity as it moved up the southeastern seaboard, abruptly filled 12 mb. in the 24-hour period of September 27–28 (figs. 4A, 5A). This filling may also be detected by comparing sets of values of the 500-mb. heights and 1000–500-mb. thicknesses. It can best be explained by the fact that the upper-air divergence and cyclonic vorticity over the storm were too weak to compensate for the sum of frictional and inertial convergence in the low layers. Concurrently, the winds aloft were too light to transport the colder air from the west fast enough to overcome the filling although they were successful in retarding the trough.

On September 27 (fig. 4B), the thermal trough previ-

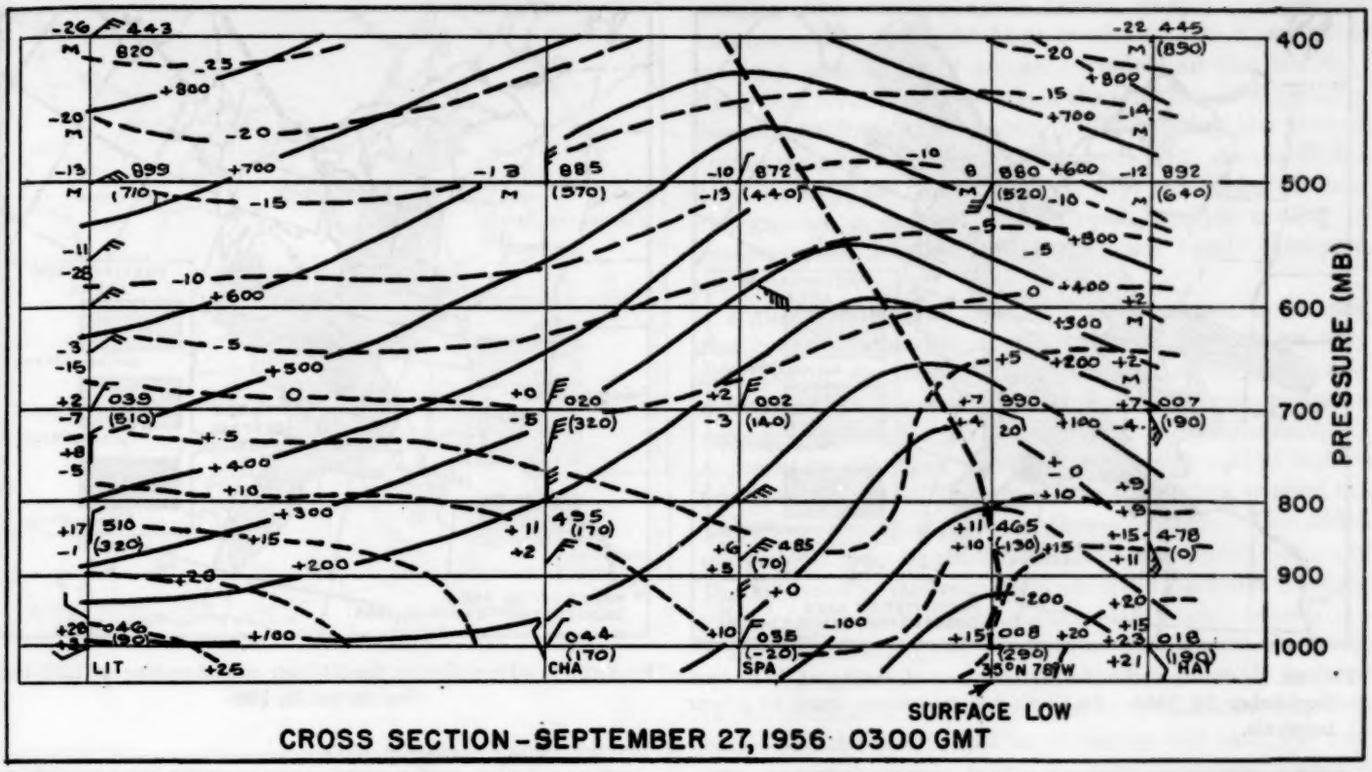

FIGURE 8.—Vertical cross section through center of Low, 0300 GMT, September 27, 1956. Note change in slope of trough and the cold air advection in lower levels compared to figure 7. LIT = Little Rock, Ark., CHA = Chattanooga, Tenn., SPA = Spartanburg, S. C., and HAT = Hatteras, N. C.

ously mentioned in the discussion of retardation was over the Ohio River Valley, about 300 miles west of the Low. Twenty-four hours later, on September 28 (fig. 5B), the cold air, which had lowered heights in the rear of the trough, was then in phase with the contours. Meanwhile a warm ridge was advancing southeastward across the Great Lakes. The accompanying anticylconic vorticity and warm air advection ahead of this ridge raised heights over the Low and caused the trough to be displaced eastward (fig. 6B). At the surface, with the High over New England rapidly falling away and the Low near southeastern Virginia weakening considerably, the strong gradient had all but completely vanished. The cyclone then moved somewhat faster northeastward during the next 24 hours to a position just southeast of Nantucket, Mass. (fig. 6A), ending the heavy rains and the threat of high tides along the New England Coast.

5. TRANSFORMATION

The temperature distribution near the surface and up to 700 mb. is quite uniform in a hurricane (Jordan and Jordan [7]). Above 700 mb. the warm-core characteristics become well marked with temperatures in the center averaging as much as 10° C. warmer than the outside. The absence of this characteristic soon after Flossy entered the coast and moved across the Florida Panhandle, indicated that the storm had rapidly begun losing its hurricane structure. Figure 2C shows that the storm was advancing over an area where thickness values were already below normal. As it is probable that a hurricane is maintained by the latent heat energy released from the ascending moist tropical air (e. g. Mohri [8]) it seems that this intrusion of cooler air into the storm circulation effectively reduced the supply of latent heat and thereby caused the storm's degeneration, marked by a decrease in wind speeds. That the dissipation of hurricane winds is controlled primarily by the energy budget, and not by the frictional effect, has been pointed out by Hubert [6].

While it is difficult to determine exactly when the hurricane began to acquire extratropical distinction, cross sections through the center of Flossy (figs. 7 and 8), made 48 hours apart, clearly show differences in structure between the tropical and extratropical cyclone. In figure 7, isolines of departure (D) of pressure altitude from that of the standard atmosphere (Bellamy [1]) on September 25 indicate that a practically vertical core of warmer temperatures was over the center. It is suspected, however, that because of the very slight tilt of the core axis near 500 mb., the hurricane was nearing its last stage as a pure tropical storm.

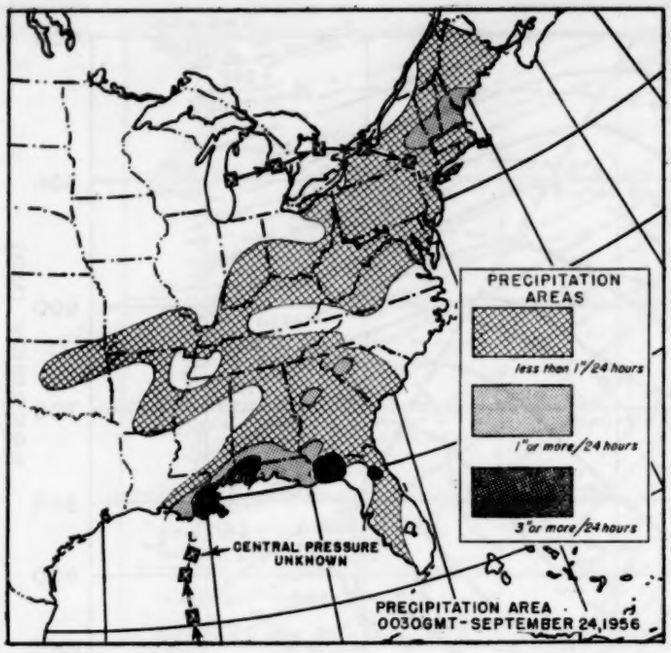

FIGURE 9.—Precipitation for 24-hour period ending at 1230 GMT, September 24, 1956. Small x's indicate storm track at 6-hour intervals.

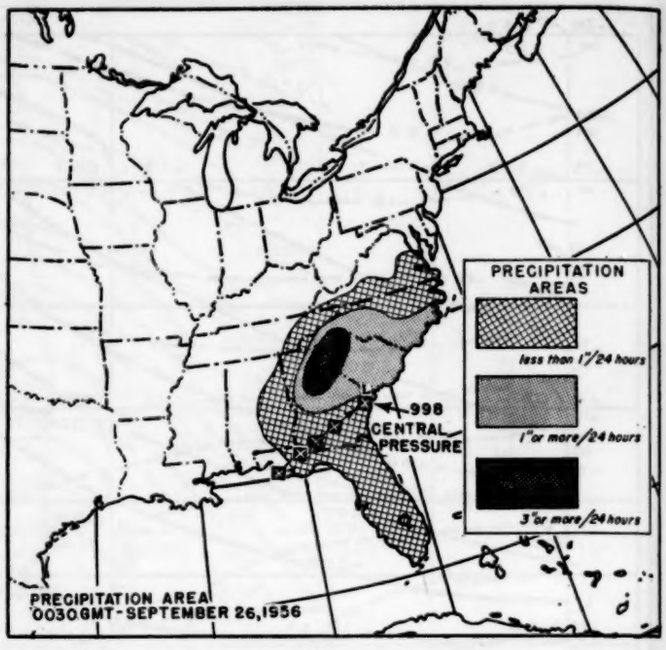

FIGURE 11.—Precipitation for 24-hour period ending at 1230 GMT, September 26, 1956.

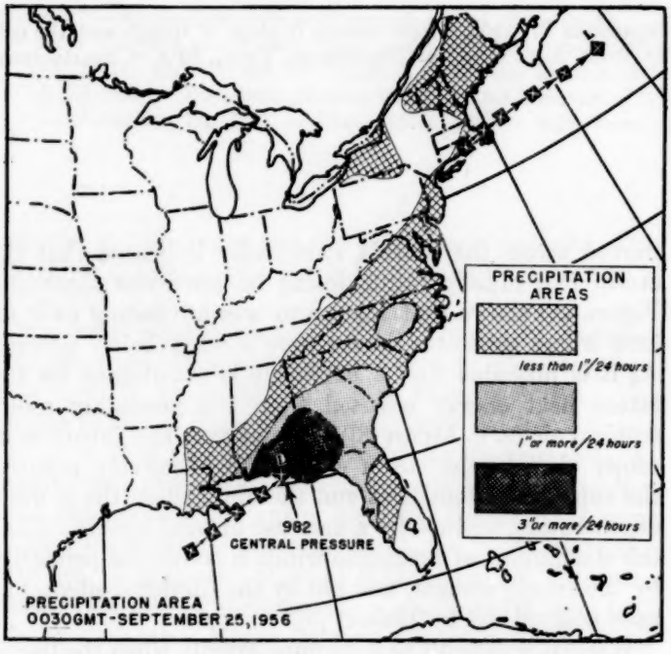

FIGURE 10.—Precipitation for 24-hour period ending at 1230 GMT, September 25, 1956.

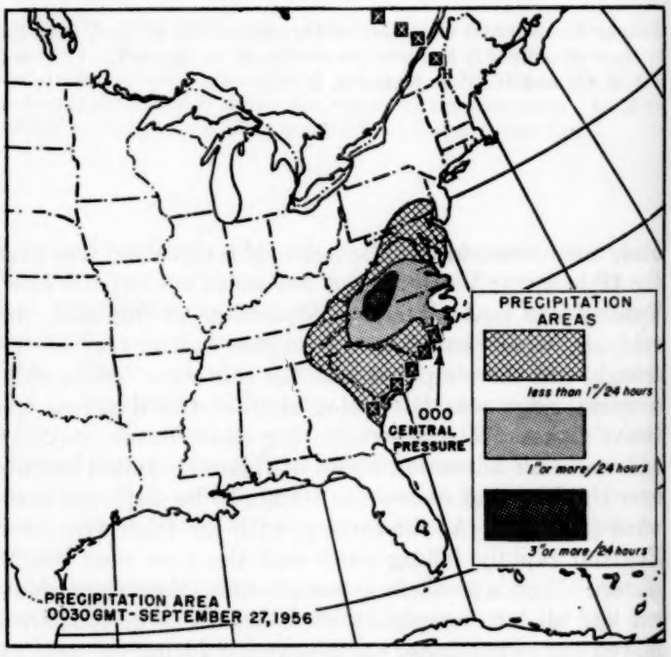

FIGURE 12.—Precipitation for 24-hour period ending at 1230 GMT, September 27, 1956.

The cross section of September 27 (fig. 8), when the storm was centered near Wilmington, N. C., leaves little doubt that Flossy had at that time the extratropical characteristics apparent in many wave patterns. The axis of the Low core, from the surface to the 500-mb. level, then had a definite slope to the west. There was also quite a difference in the thermal field: (1) the 500-mb. temperature over the Low was now 8° C. colder than it was on September 25; (2) strong cold air advection was present below the 700-mb. level west of the Low; and (3) the colder temperatures above the 700-mb. level were advancing eastward toward the Low; this, incidentally, eventually made it a cold Low. The isothermal patterns on the 500-mb. charts of September 25 (fig. 2B) and September 27 (fig. 4B) also clearly demonstrate the structural differences in the types of cyclones.

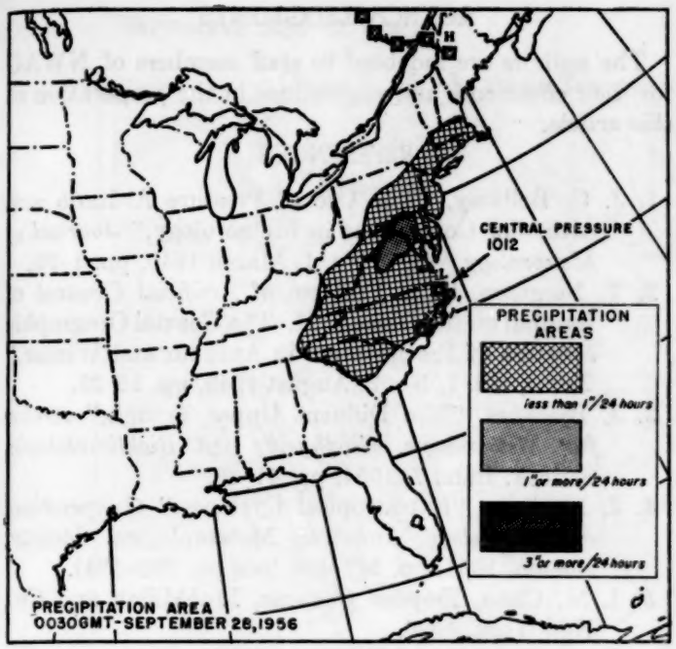

FIGURE 13.—Precipitation for 24-hour period ending at 1230 GMT, September 28, 1956.

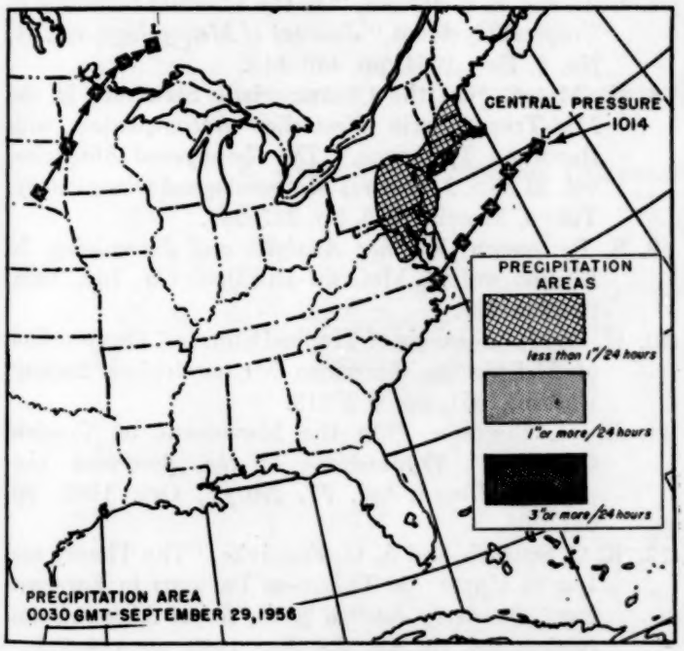

FIGURE 14.—Precipitation for 24-hour period ending at 1230 GMT, September 29, 1956.

6. PRECIPITATION

According to Cline [5], tropical cyclones in the Gulf of Mexico have the greatest precipitation intensity in front of and somewhat to the right of a line along which the storm is moving, with relatively little precipitation in the rear half. This is due, he states, to the winds of high velocity moving through the right rear quadrant and converging with weaker winds having greater cross-isobar components in the right front quadrant. As Flossy with its deep moist layer of unstable tropical air and low condensation level first approached the Gulf Coast, orography became an important factor in determining the overall total precipitation amounts (Bergeron [2]). As the southerly winds forced the tropical air over the colder air near the ground, it did not require much upglide cooling to condense the moisture from the already nearly saturated air.

Figure 9 shows that, as the hurricane neared Louisiana, the heaviest amounts of precipitation were in an area neighboring the coast. The frictional effect previously mentioned in the recurvature discussion was probably most responsible for the 3-inch isohyet found immediately adjacent to the shore. As the cyclonically curved isobars traversed the coast, the winds, due to friction, crossed the isobars at a greater angle toward lower pressure. This added convergent zone increased the upward vertical motion of the air parcels, which in turn caused saturation to occur more rapidly and precipitation to fall more intensely.

On the following day, September 25 (fig. 10), the maximum precipitation area continued to lie directly in front of the hurricane. It is difficult to determine exactly which cause had the most effect in producing this rain; the convergence suggested by Cline, the ascending motion caused by friction, or the general upslope motion of the warm tropical air overriding the colder air over land. All these elements were still present on the 25th.

The areas of rainfall shown in figures 9–14 of course are not synoptic with the indicated centers, but instead cover a 24-hour period beginning 12 hours prior to and ending 12 hours after the surface map time. For all intents and purposes this does not affect the general direction of maximum precipitation, although the extent of the area and the amounts of total rainfall should be adjusted downward to represent synoptic patterns.

As Flossy slowly moved across southern Georgia to the South Carolina border on September 26, the general size of the area of heavy rains (fig. 11) remained relatively the same despite the fact that the source of moist tropical air responsible for the precipitation was being cut off as the cold air entered the circulation from the west. The extension of the quasi-stationary polar front into the storm center may be a partial explanation. According to Petterssen [9], when the orographic upglide is superimposed upon the general frontal upglide, there is a consequent increase in the rates of condensation and precipitation. This added lift given to the overrunning air could have been enough to compensate for any deficiencies in the moisture content and temperature of the modifying tropical air mass.

After Flossy became extratropical, although the whole general area approximately 150 miles to the north of the Low had precipitation amounts in excess of 1 inch per 24 hours, only those regions on the eastern slope of the Appalachians had totals of 3 inches per 24 hours (figs. 11

and 12). The rate and hence the total amount of precipitation depended largely upon the strength of the flow of the moist unstable air mass normal to the mountain barrier. This capacity to produce heavy rains became more evident with time as the easterly flow north of the center and normal to the mountains steadily increased. The resulting friction and cross-isobaric flow along the windward side of this range caused convergence and ascending vertical motion, which in turn enhanced the rainfall intensity. Conversely, the divergence and descending motion on the leeward side resulted in little or no precipitation in those areas west of the higher mountain ridges.

On the following days, September 28 and 29, as the cyclone filled and moved more rapidly northeastward reducing the onshore flow, the rainfall totals tapered off. Figure 13 shows a one-inch isohyet in the vicinity of Washington D. C. just barely larger in size than the 3-inch area of the previous 24-hour period. On September 29, with the gradient along the New England coast more significantly lessened, precipitation totals fell off sharply (fig. 14). Only isolated coastal stations reported amounts in excess of one-half inch in 24 hours, most of which occurred in the first 12-hour period.

7. DESTRUCTION

From the time Flossy approached the United States until the time it moved out over the Atlantic, it left in its wake widespread damage from hurricane-force winds, high tides, and heavy rains. Above normal tides and heavy wave action battered the Gulf Coast from west of Grand Isle, La., to Tampa, Fla., and windblown sand along the beach areas drifted on highways [13]. As the storm moved over southwestern Georgia, the high winds and heavy rainfall damaged unpicked cotton and unharvested corn to the extent that while the crops were not entirely lost, the quality was greatly reduced. Of course, property damage such as unrooted trees, broken branches, and broken TV antennas was extensive but relatively minor.

Along the Atlantic Coast, damage was restricted to flooding caused by the strong onshore winds ahead and east of the storm center producing above-normal tides and wave action. However, residents of these areas were notified of the predicted high water and personal losses were reduced considerably.

In spite of the destruction left in her path, Flossy was not entirely detrimental. The heavy precipitation associated with the storm greatly relieved the drought conditions in northern Florida, Georgia, and the Carolinas. The value of these beneficial rains may even outweigh the total damage.

ACKNOWLEDGMENTS

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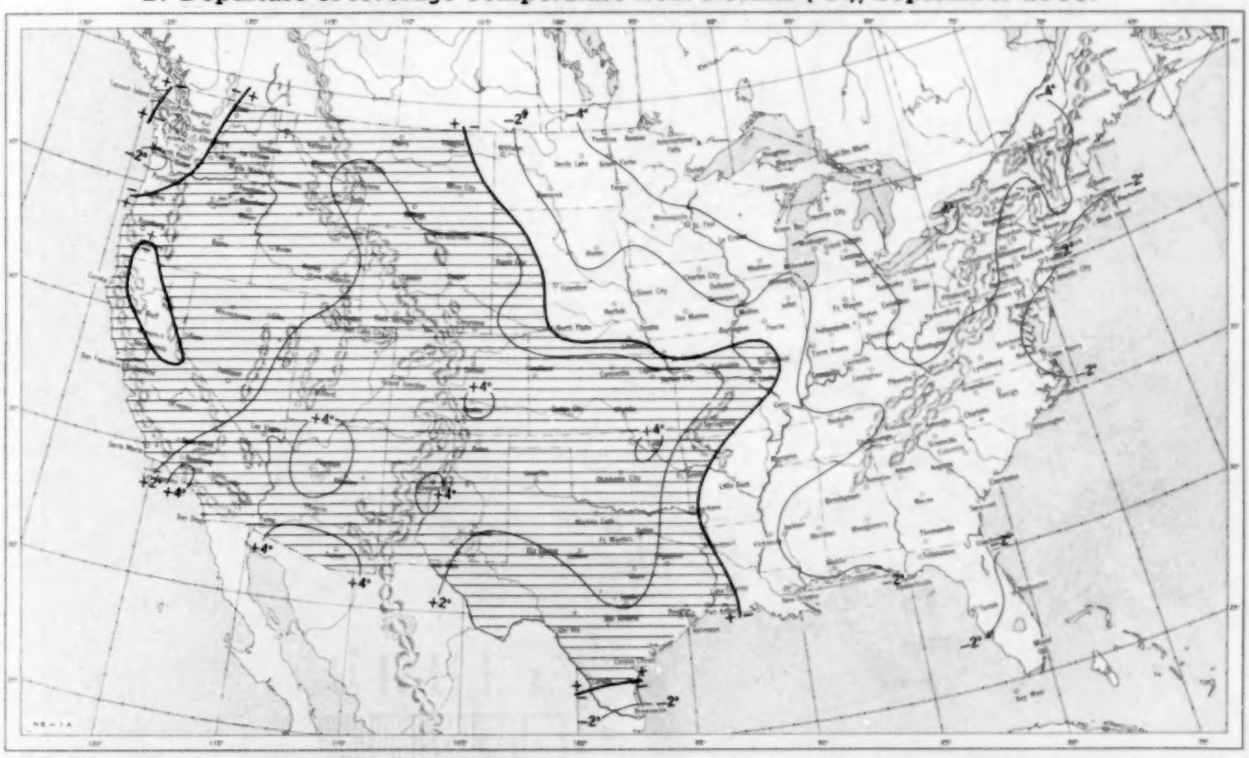
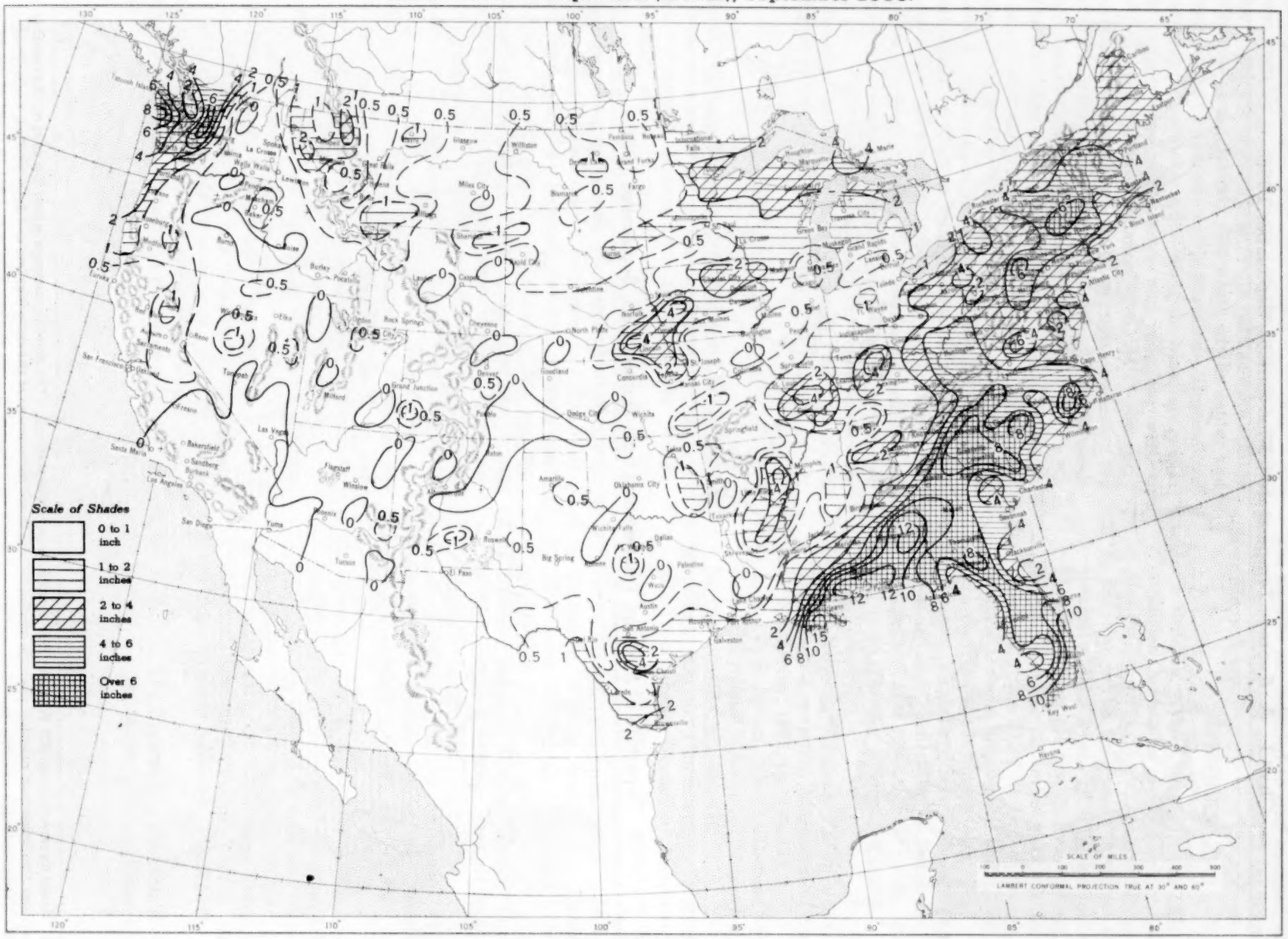
Chart I. A. Average Temperature (°F.) at Surface, September 1956.

B. Departure of Average Temperature from Normal (°F.), September 1956.



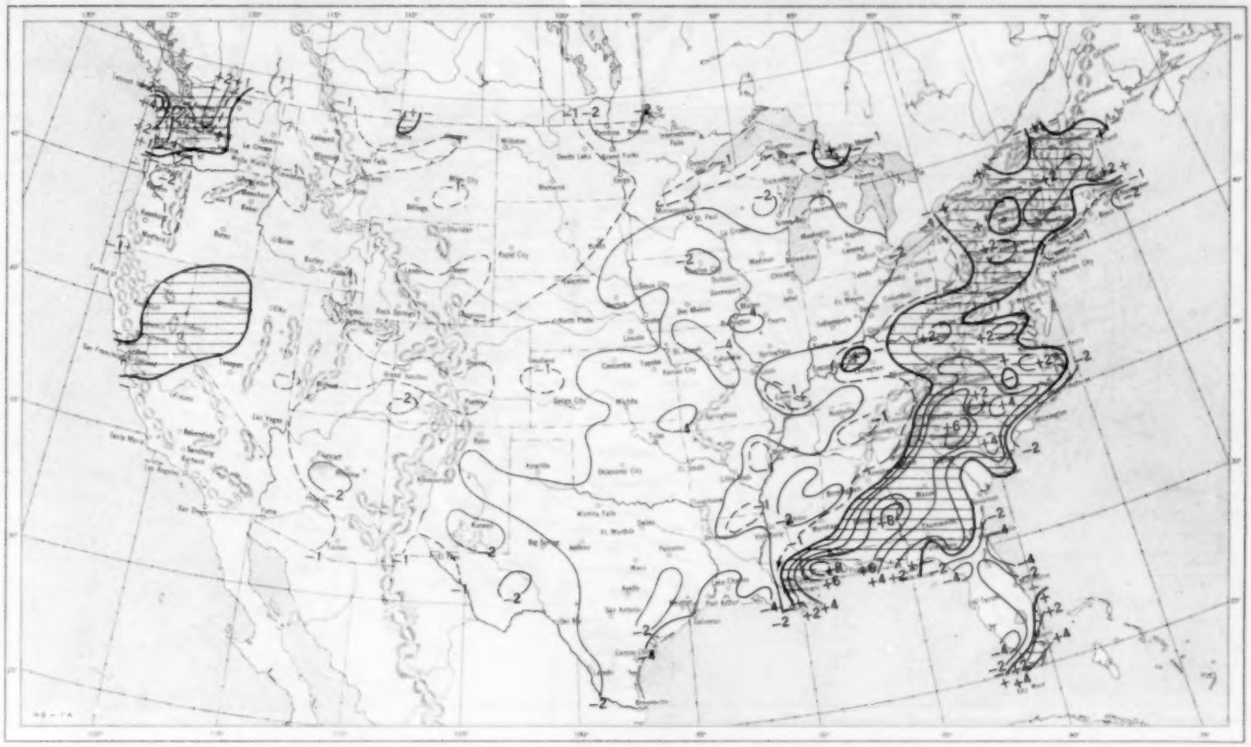
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), September 1956.

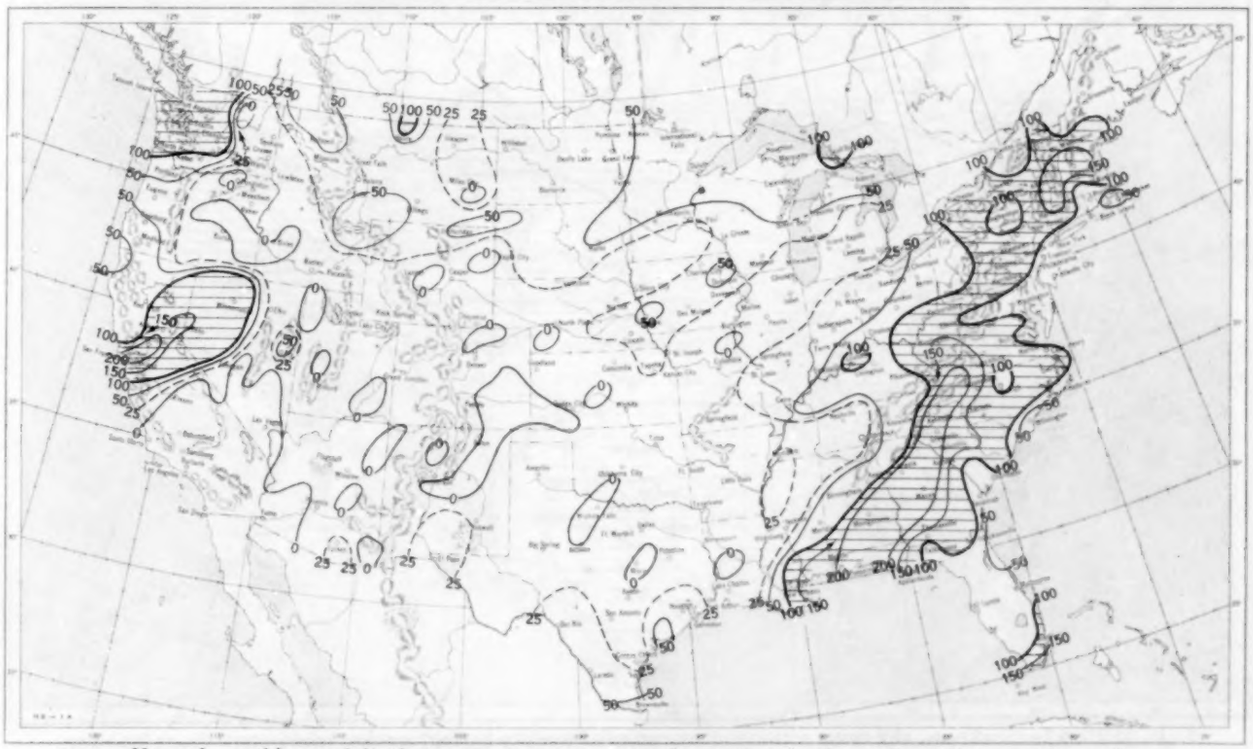

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), September 1956.

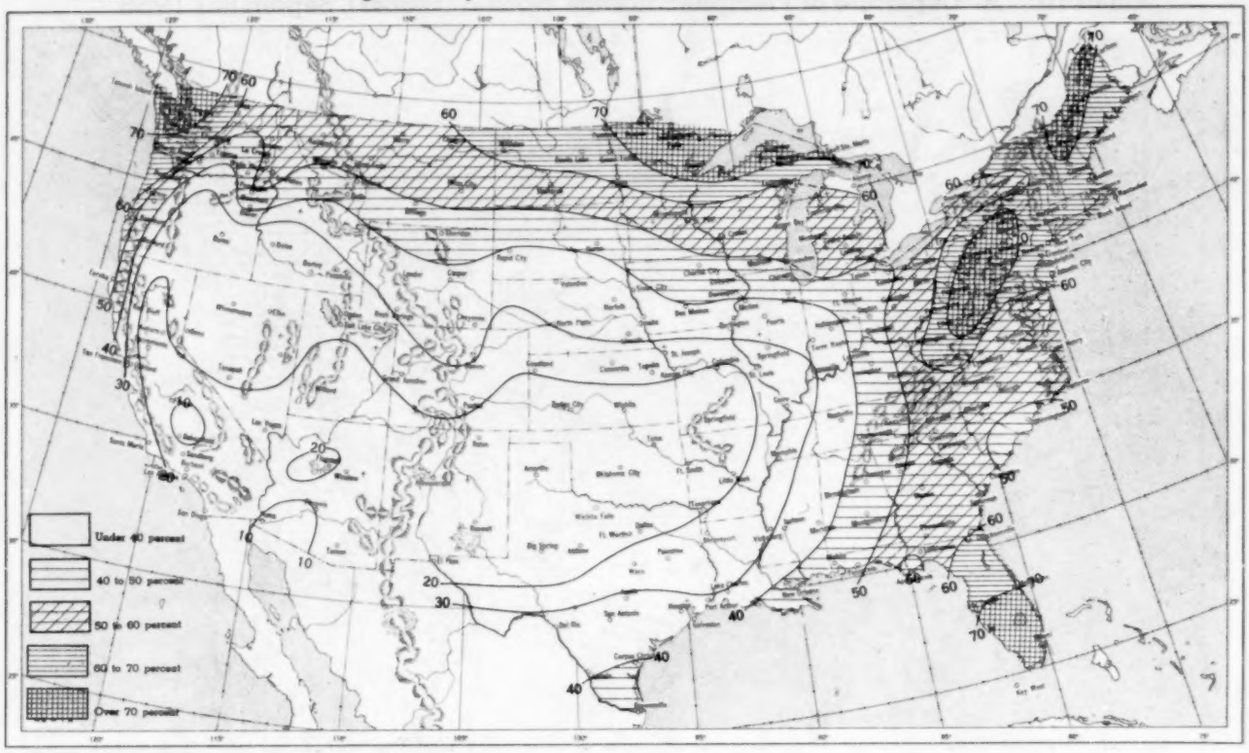


B. Percentage of Normal Precipitation, September 1956.

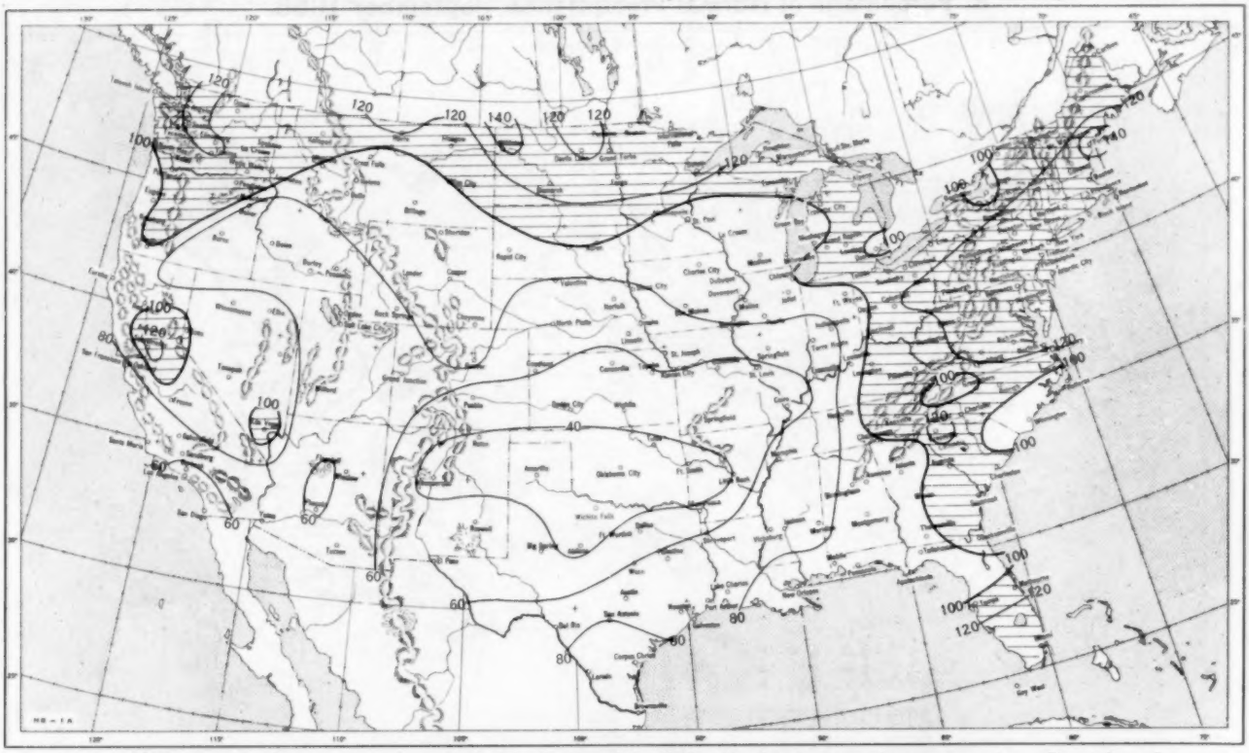


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, September 1956.

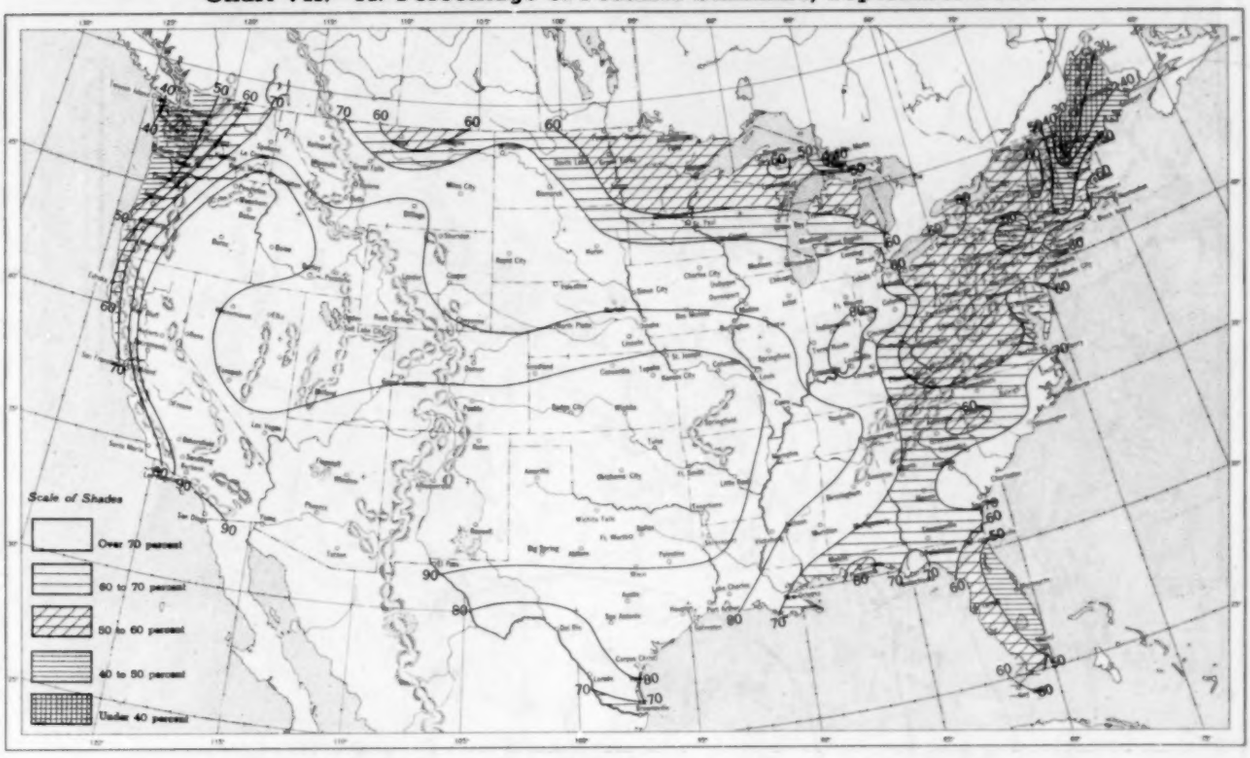


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, September 1956.

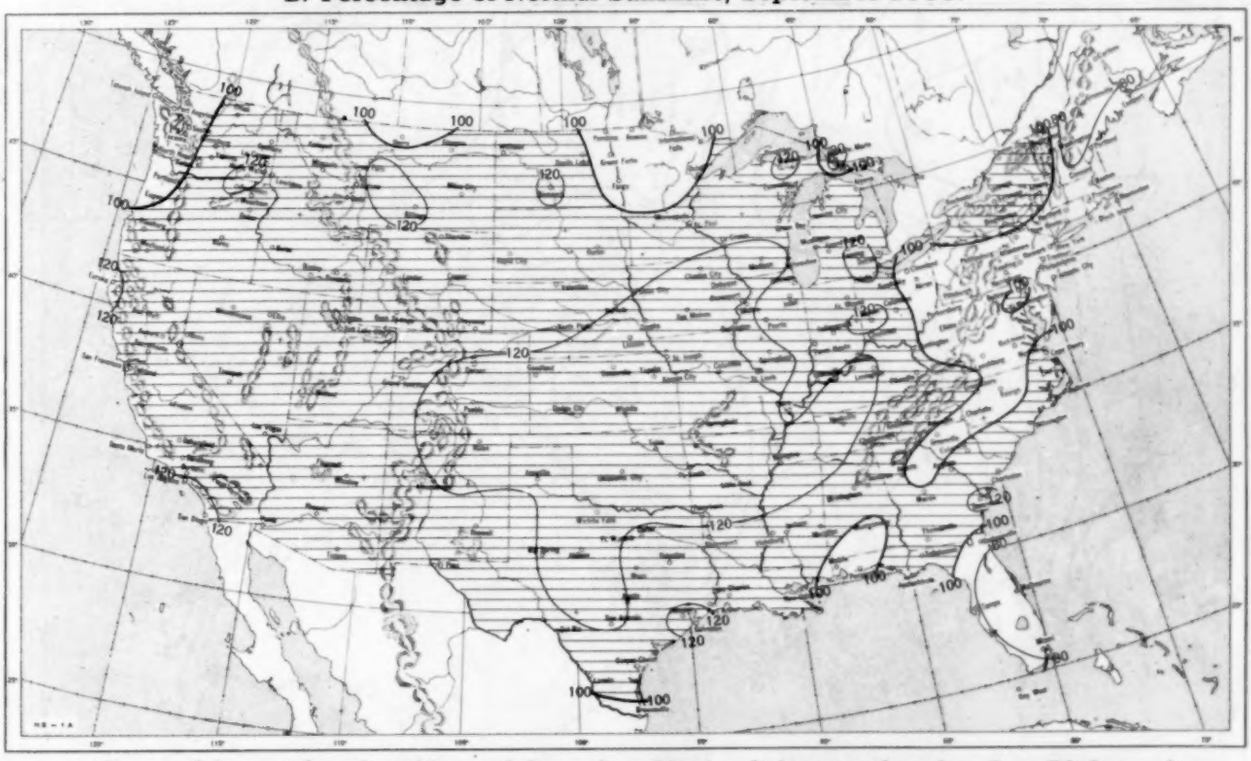


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, September 1956.



B. Percentage of Normal Sunshine, September 1956.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, September 1956. Inset: Percentage of Mean Daily Solar Radiation, September 1956. (Mean based on period 1951-55.)

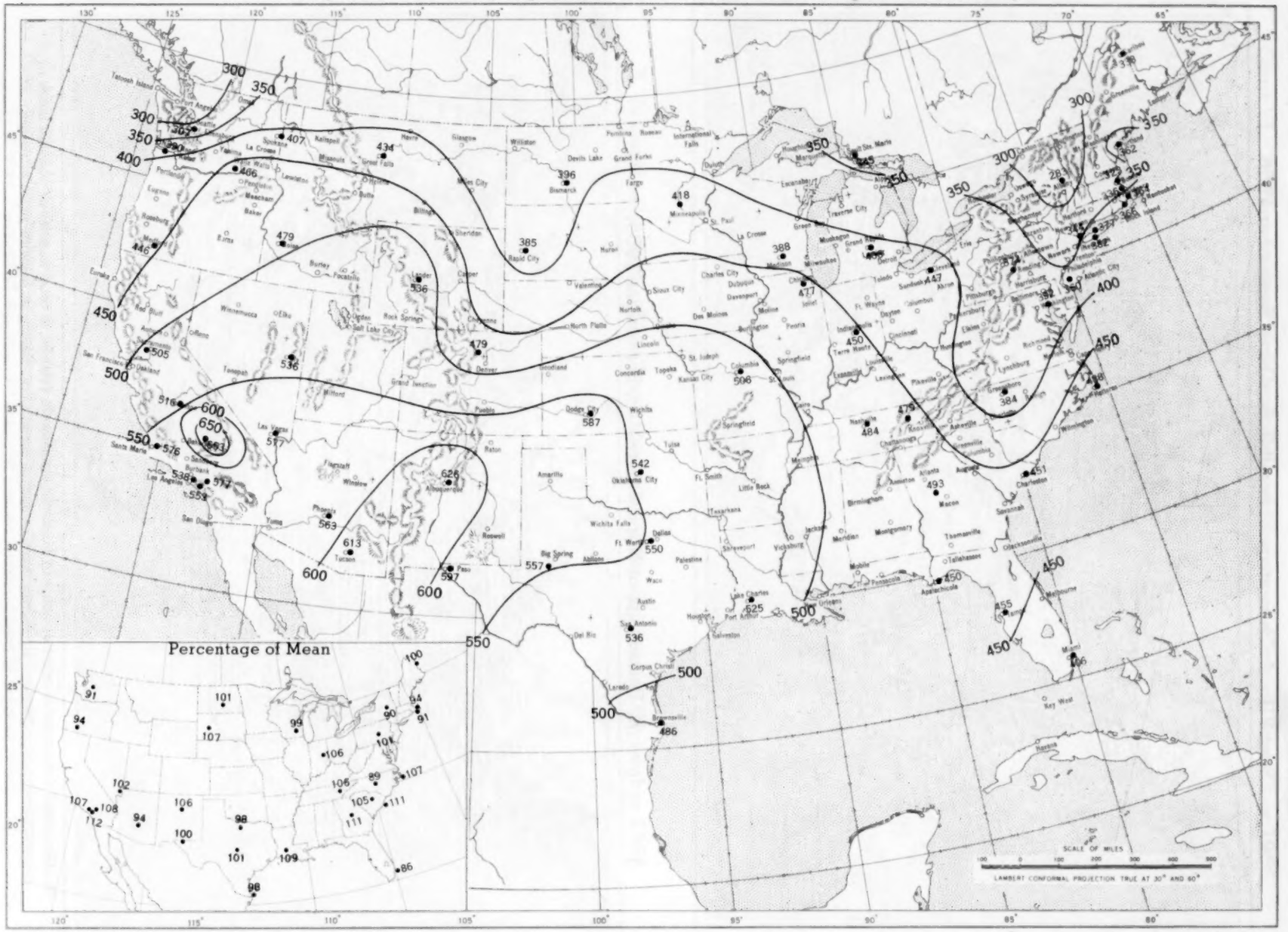
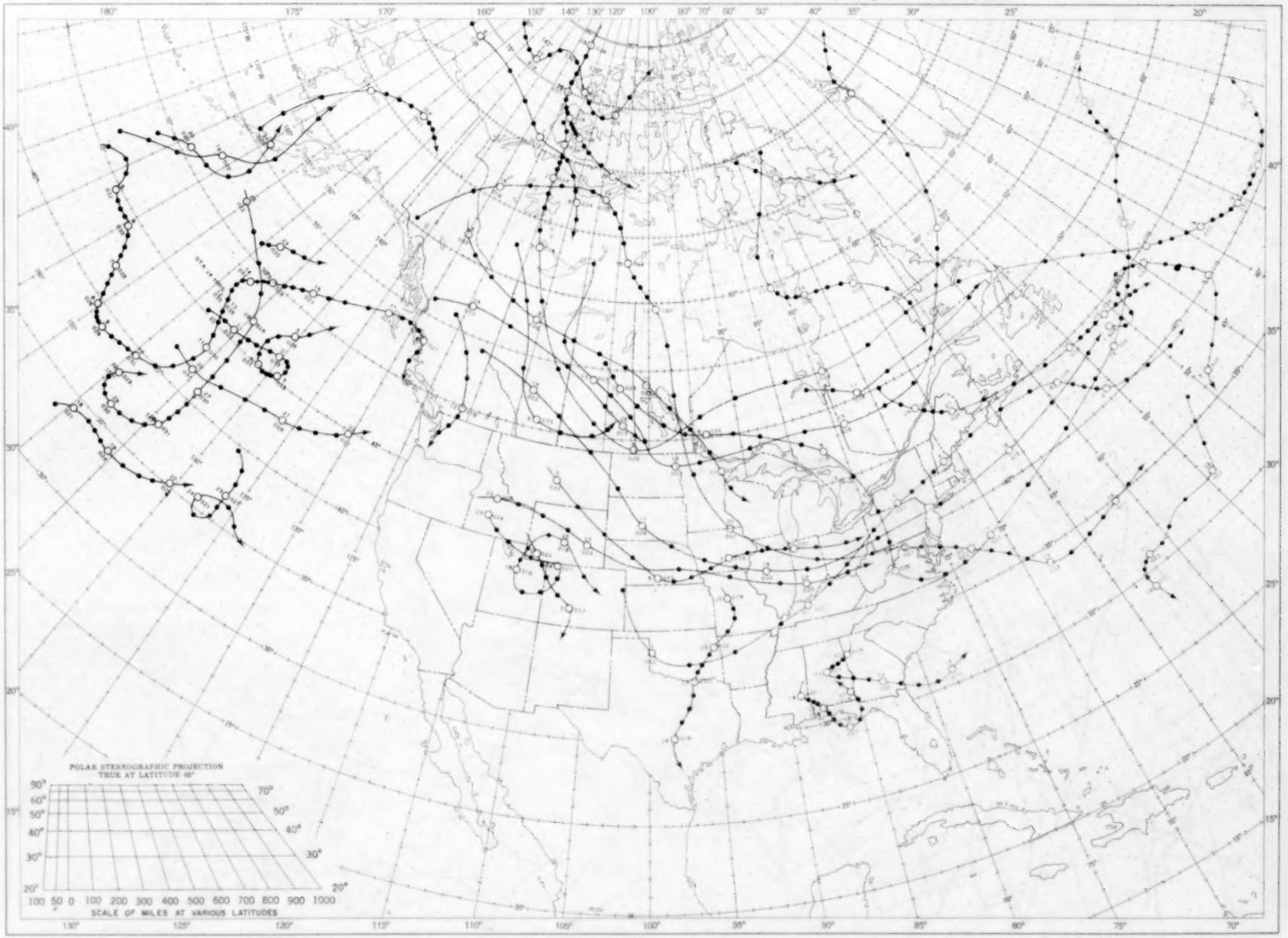


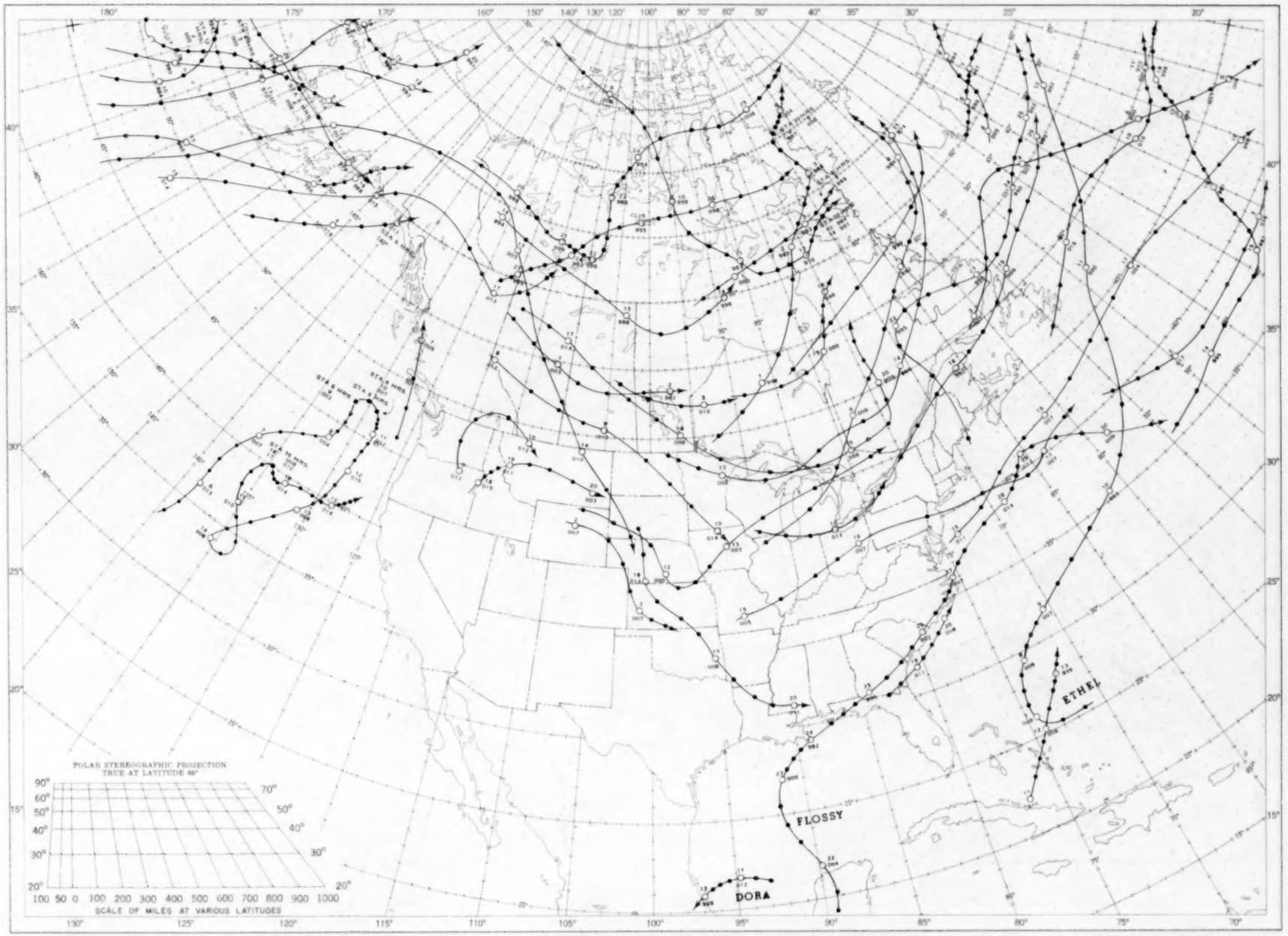
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, September 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

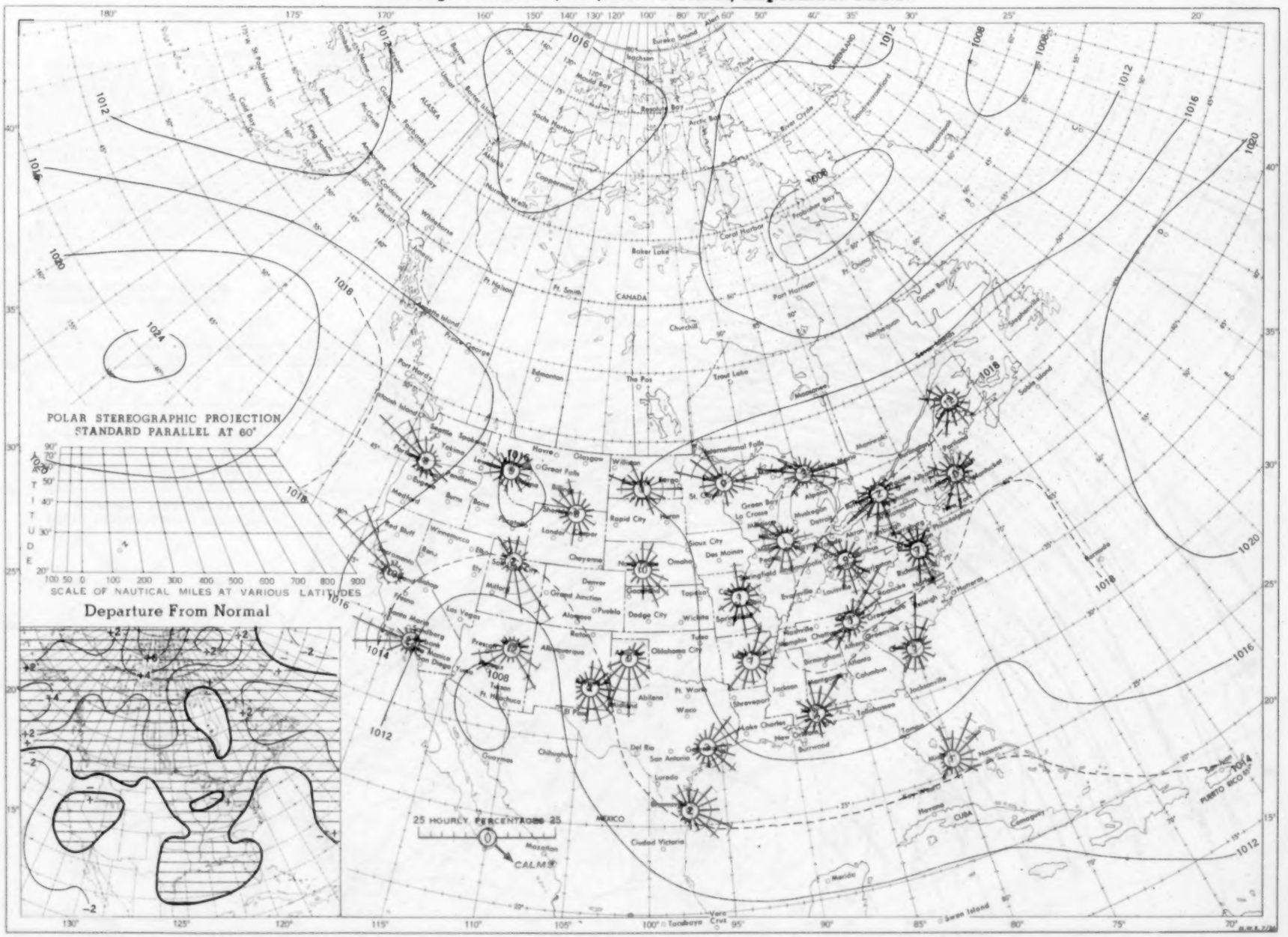
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, September 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000
FLOSSY
ETHEL
DORA

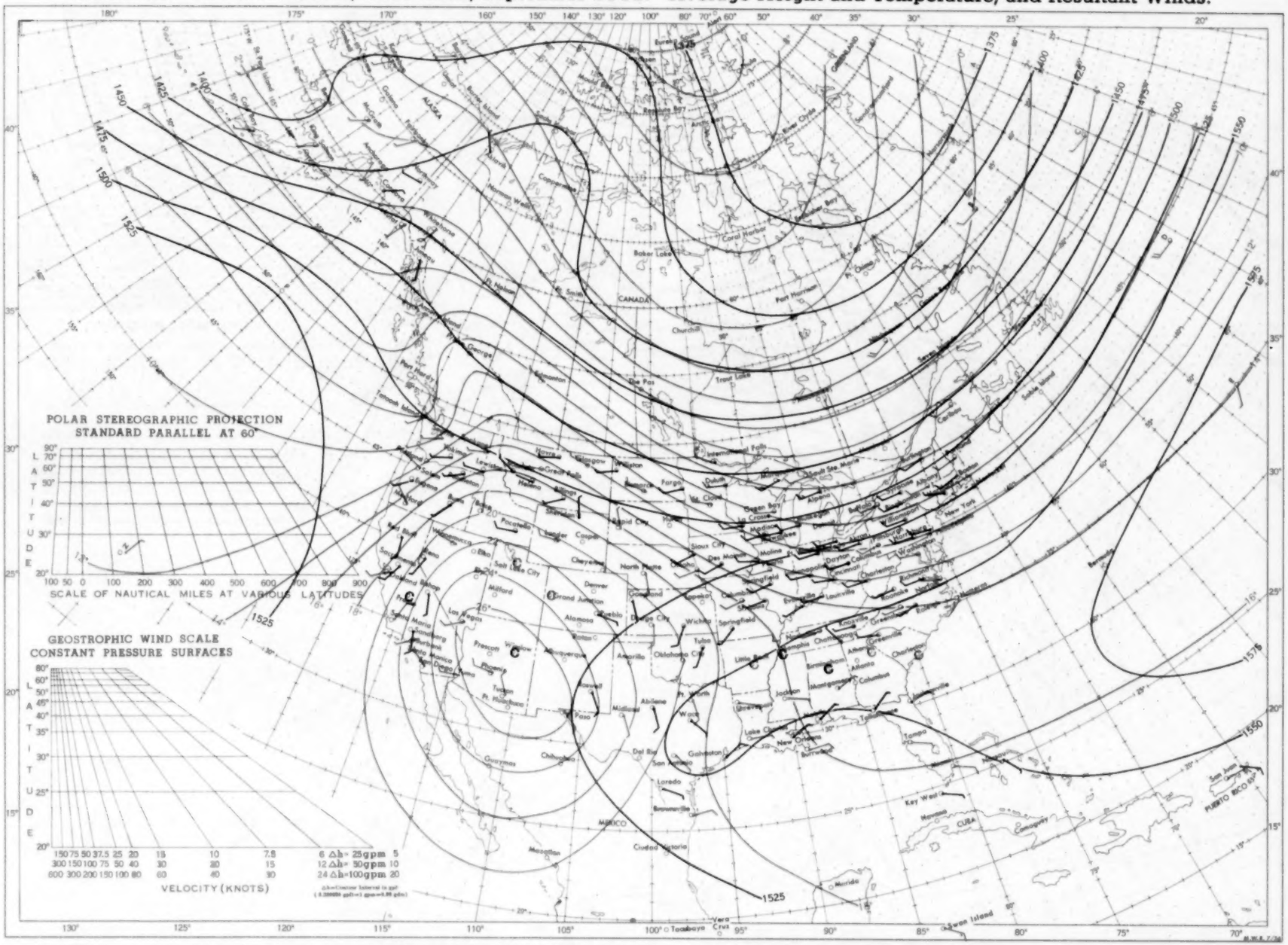
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, September 1956. Inset: Departure of Average Pressure (mb.) from Normal, September 1956.



Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

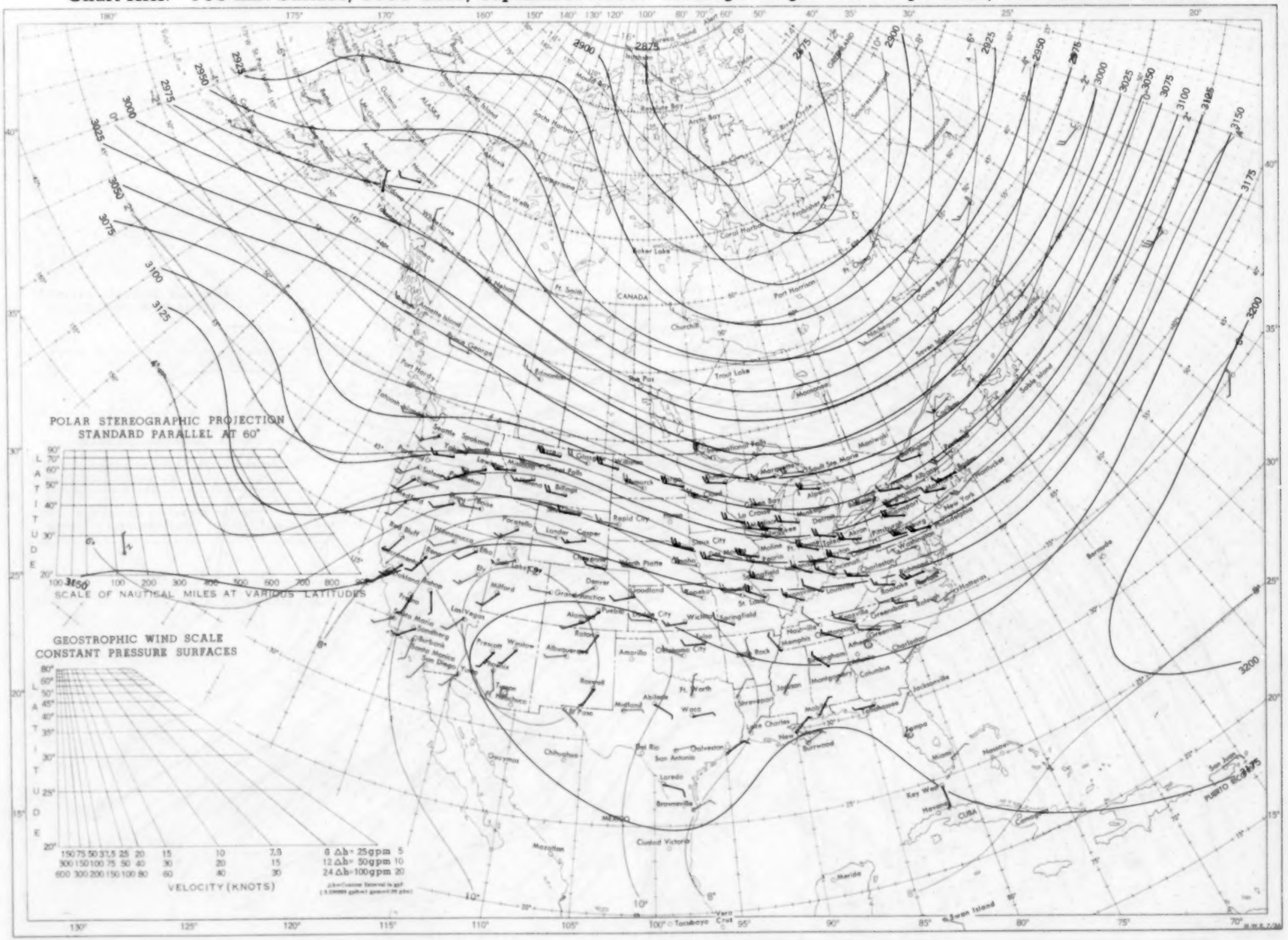
Chart XII. 850-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Winds shown in red are based on rawins taken at the indicated pressure surface and time. Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.

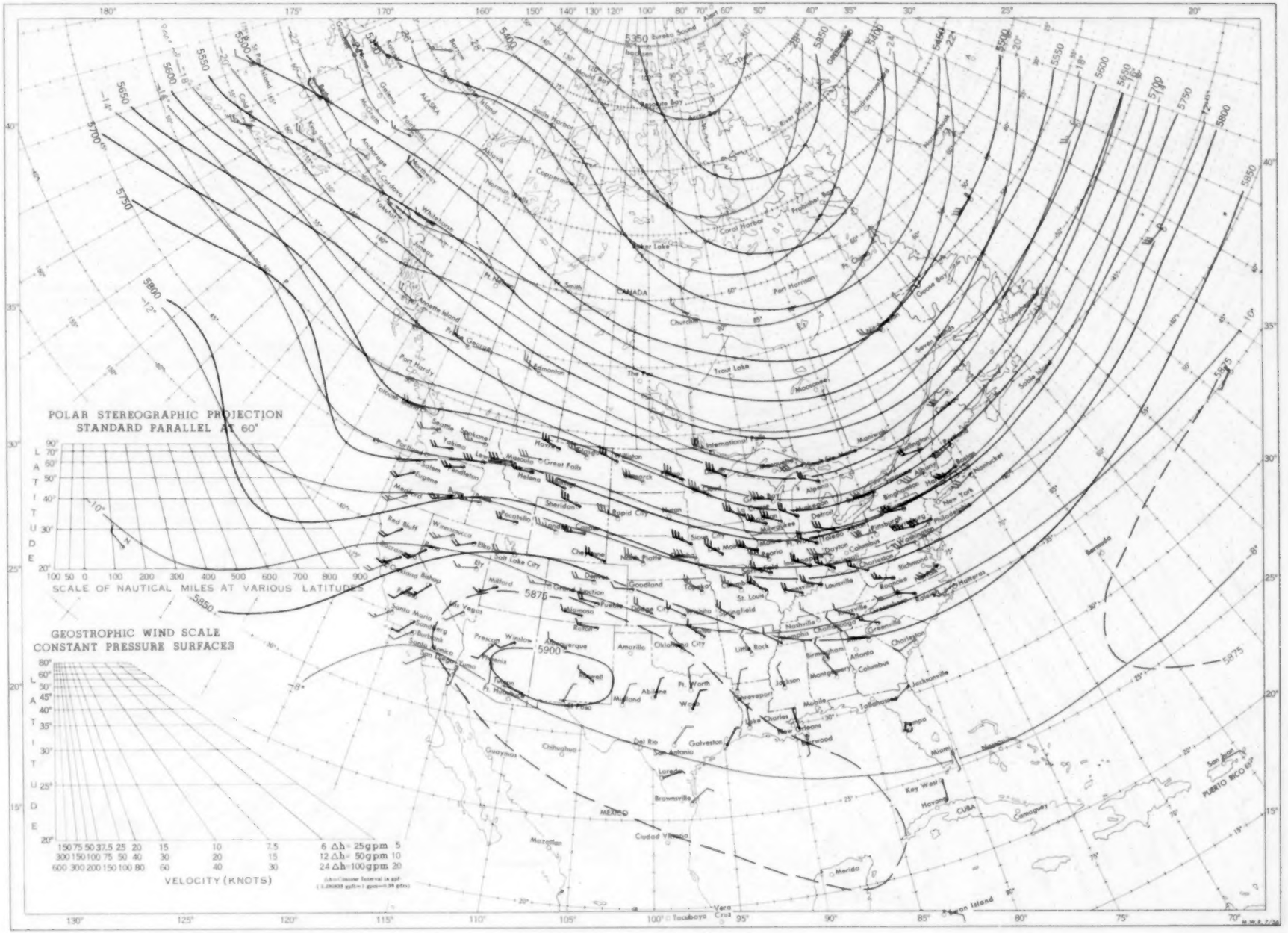
on pibals taken at 2100 GMT and are for the nearest standard height level.

Chart XIII. 700-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



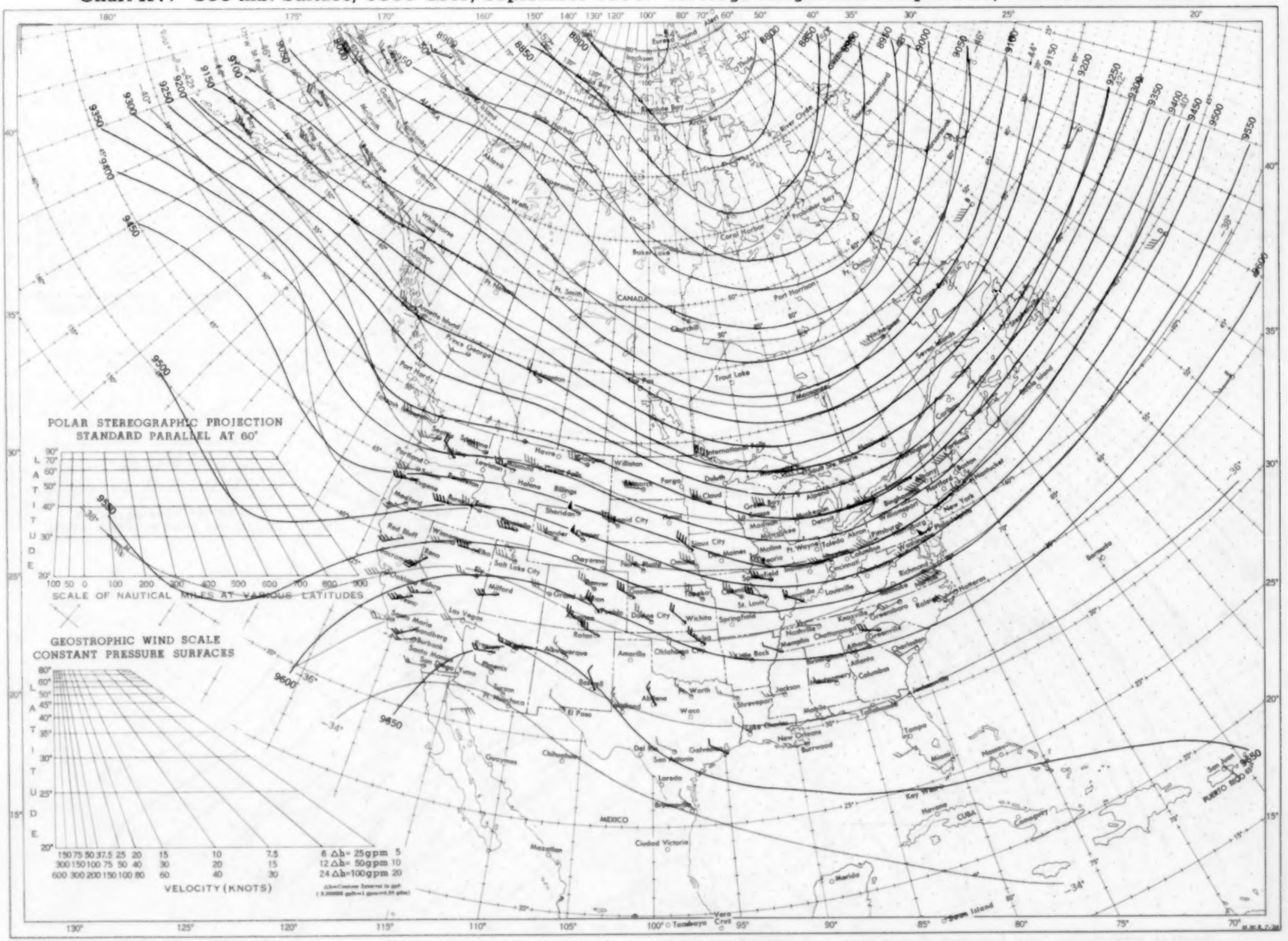
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



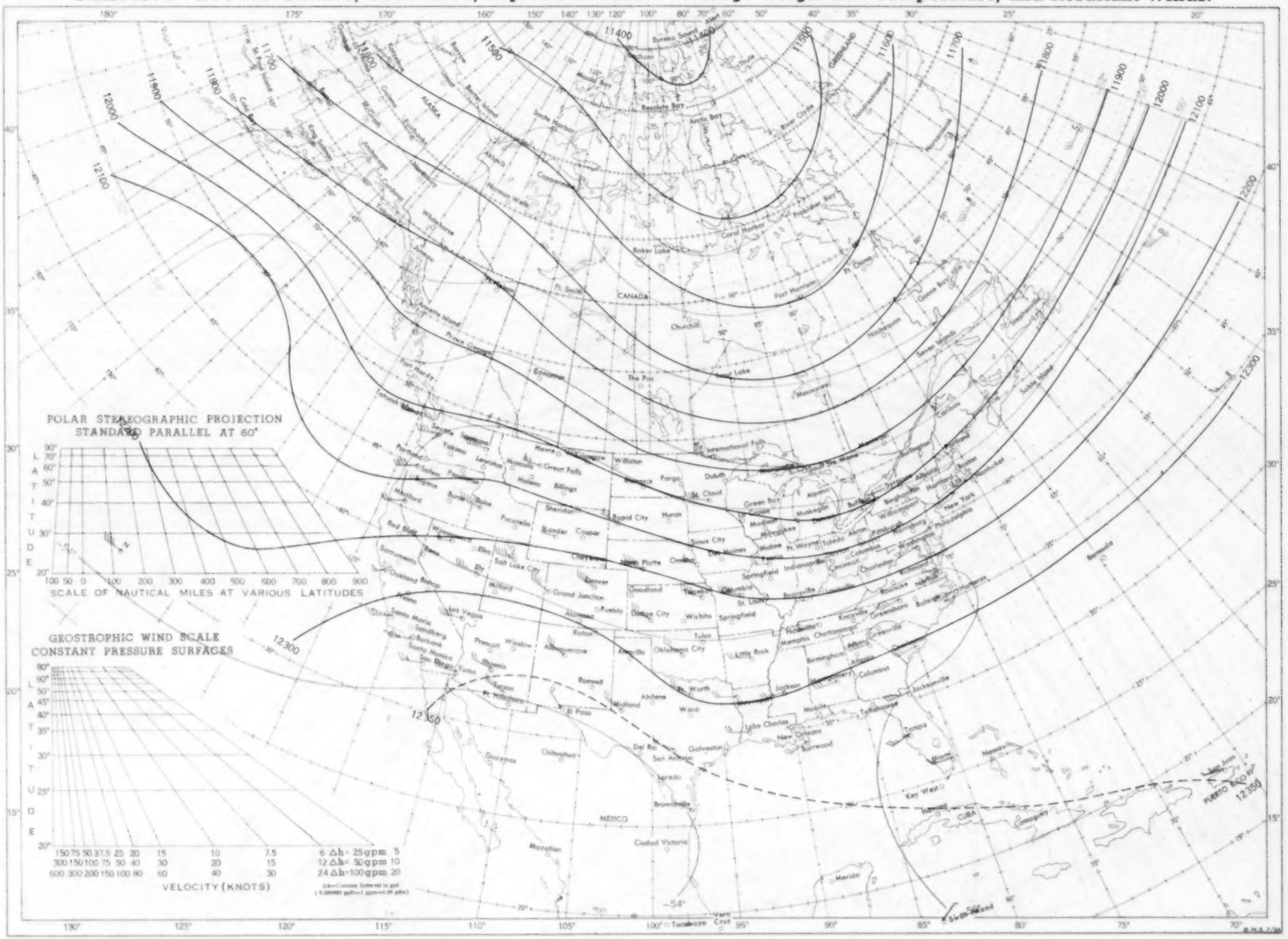
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



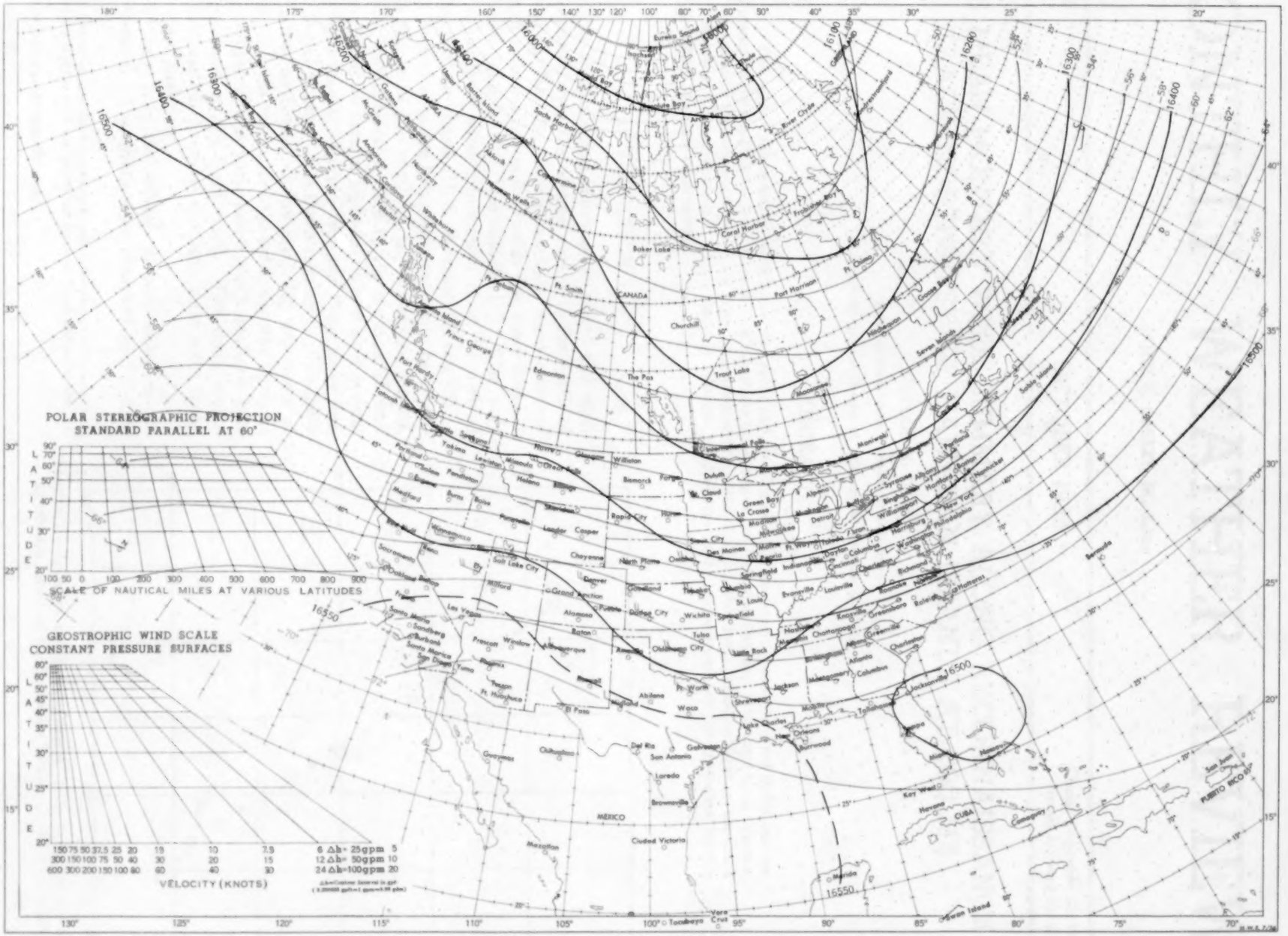
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

Chart XVII. 100-mb. Surface, 0300 GMT, September 1956. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.